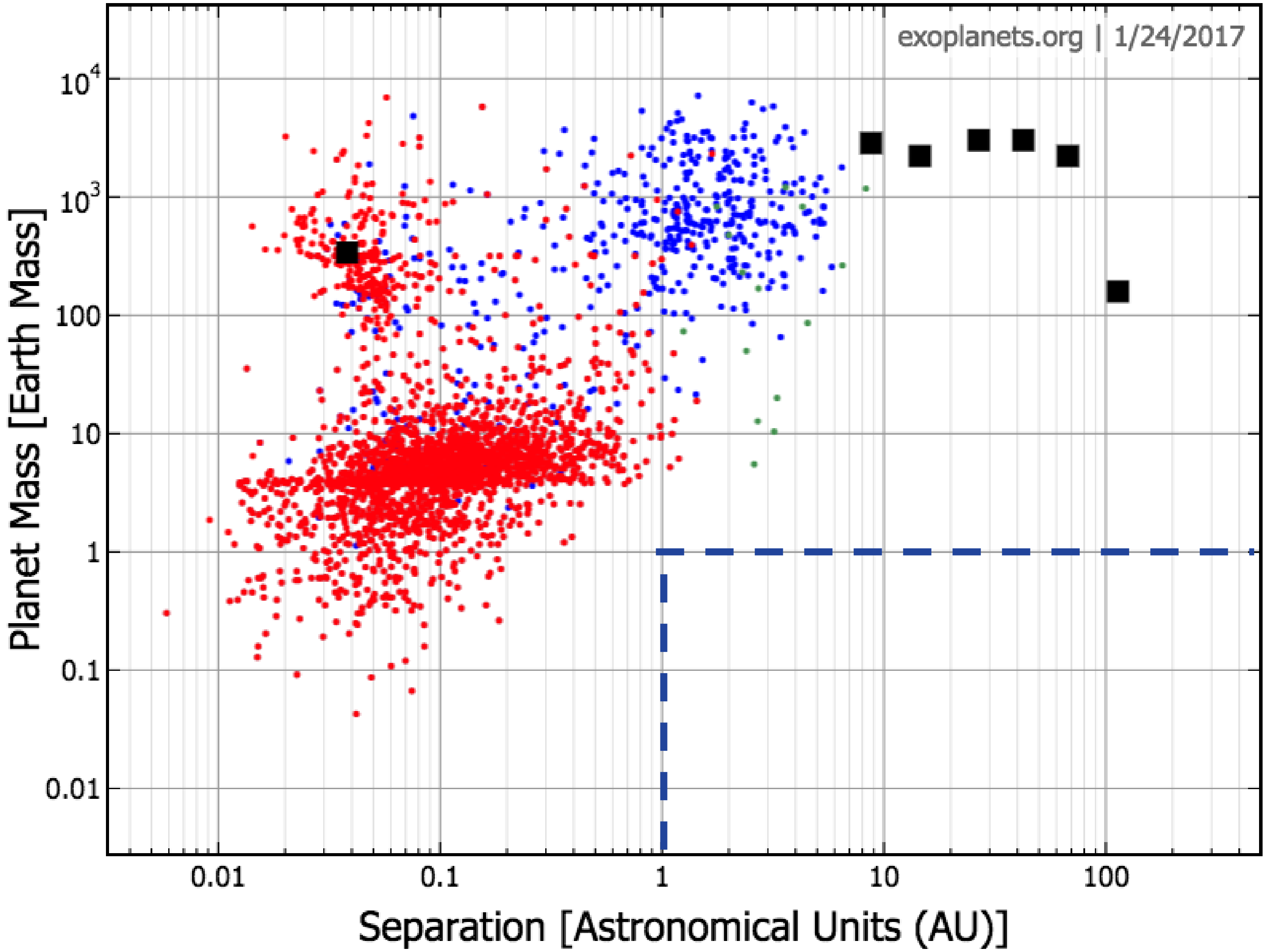
The CHARIS high-contrast integral-field spectrograph

Tyler D. Groff, Jeffrey Chilcote, Timothy Brandt, N. Jeremy Kasdin, Michael Galvin, Craig Loomis
Maxime Rizzo, Gillian Knapp, Olivier Guyon, Nemanja Jovanovic, Julien Lozi, Naruhisa Takato, Masahiko Hayashi

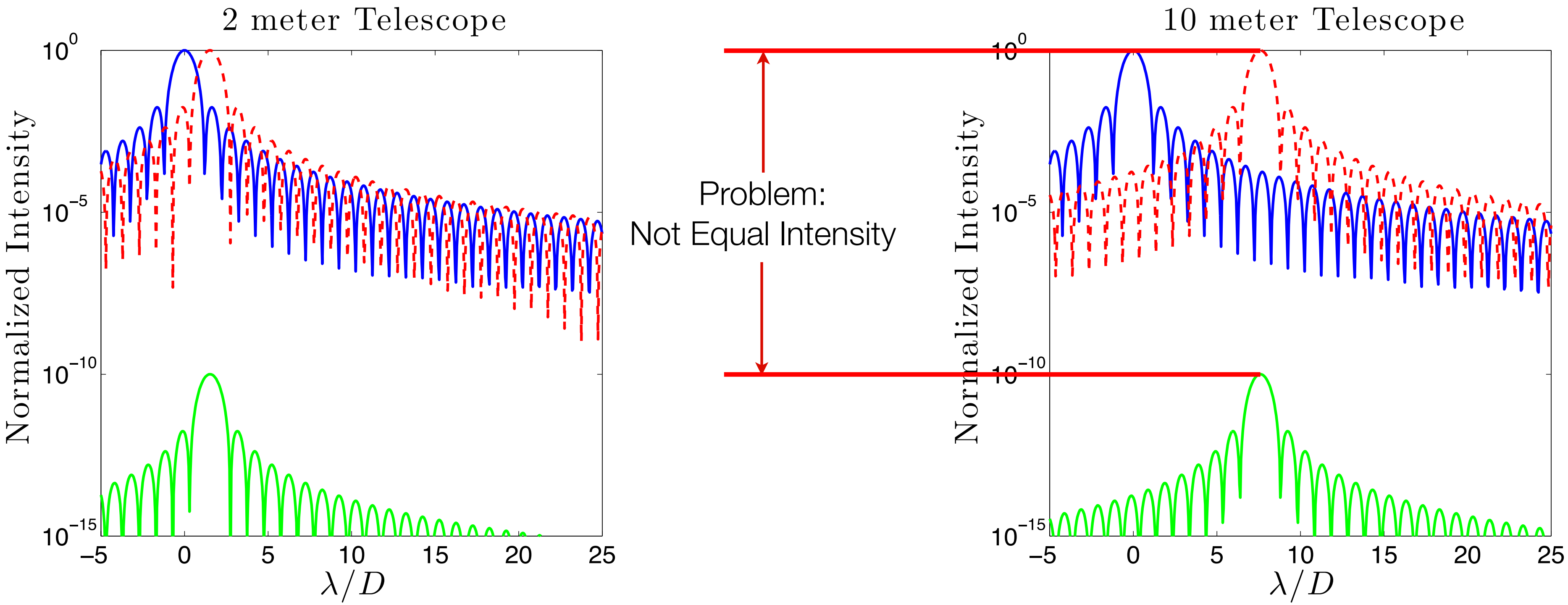
Distribution of Detection Methods

- Many planets have been detected, but largely by non-imaging techniques



What Makes Imaging Exoplanets Hard

- Separation is not the fundamental limit
- The contrast ratio of Earth is 1x10-10
- Detection at 1x10-5 contrast levels is already challenging at low inner working angle



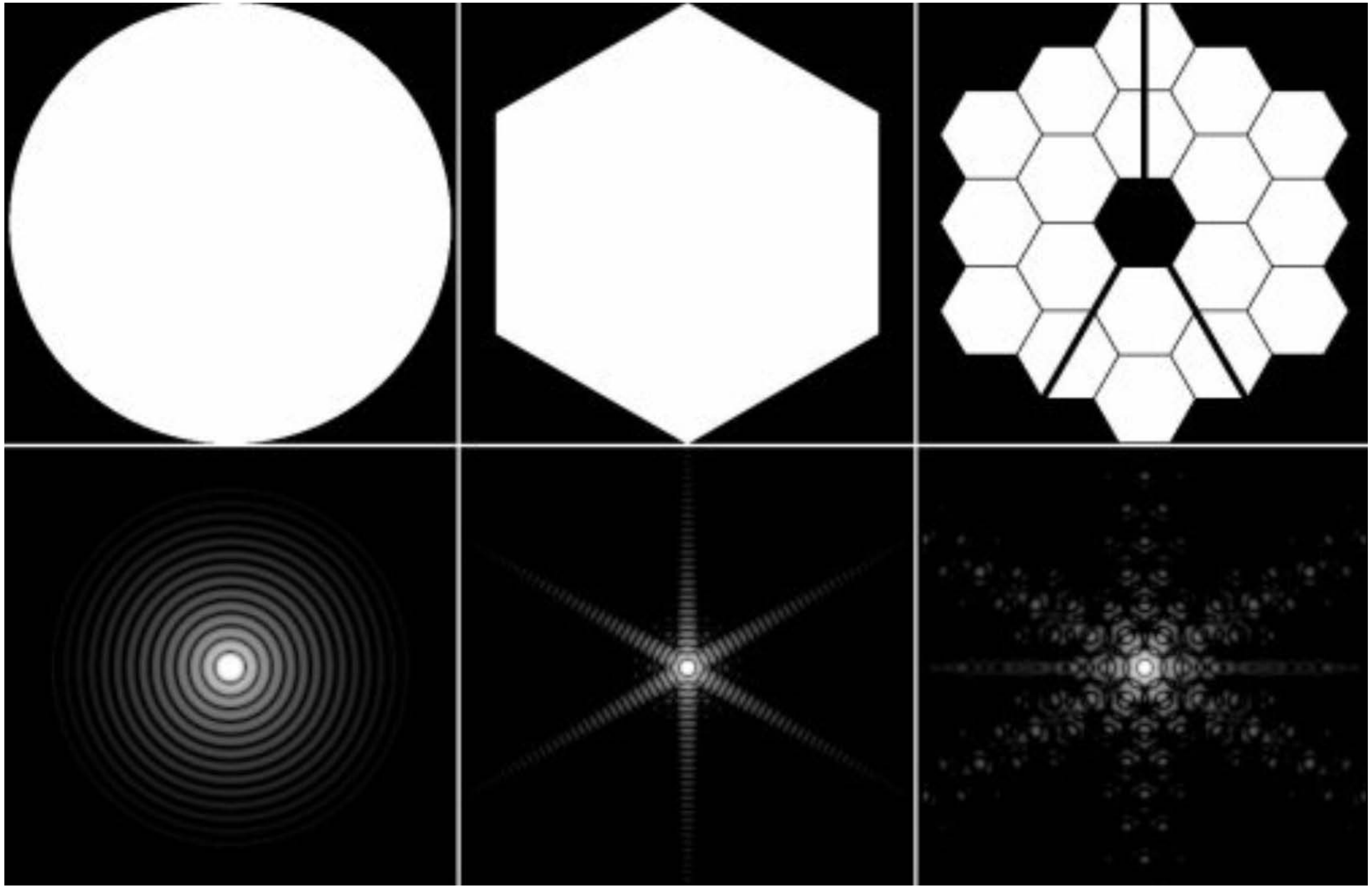
Detecting an Earth-analog, at 1 AU, Orbiting a star 10pc away requires a 2km circular aperture

Effect of Aperture

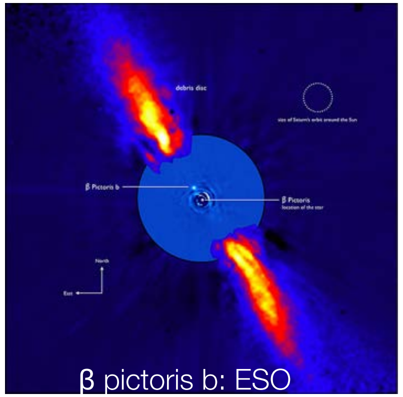
Classical Round Aperture | Hexagonal Aperture | JWST Aperture

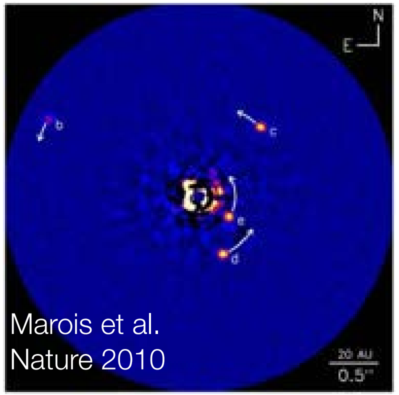
Pupil Plane

Image Plane

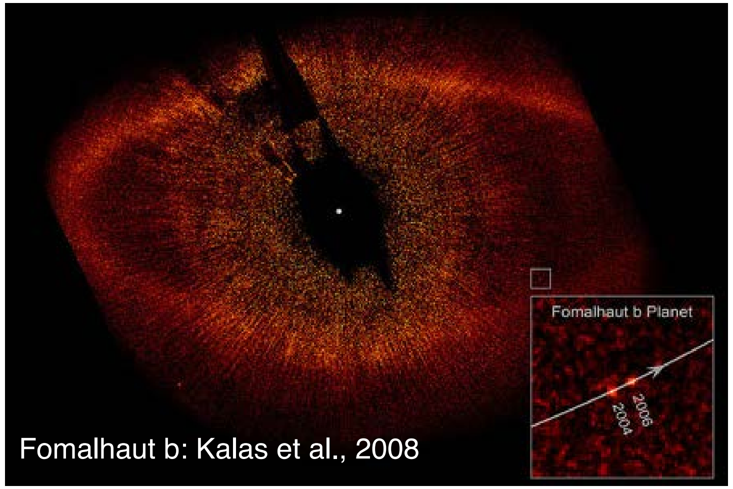


- HR8799 b: 68 AU, ~2,200 M⊕ (2008)
- HR8799 c: 38 AU, ~3,200 M⊕ (2008)
- HR8799 d: 24 AU, ~3,200 M⊕ (2008)
- HR8799 e: ~14.5 AU, ~2,800 M⊕ (2010)
- β pictoris b: 8.5 AU, ~2,500 M⊕ (2008)
- Fomalhaut b: 115 AU, ~1000 M⊕ (2008)
- 1RXS J160929.1-210524 b: ~330 AU, ~2542 M⊕ (2008)

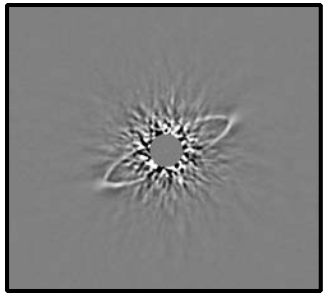

β pictoris b: ESO



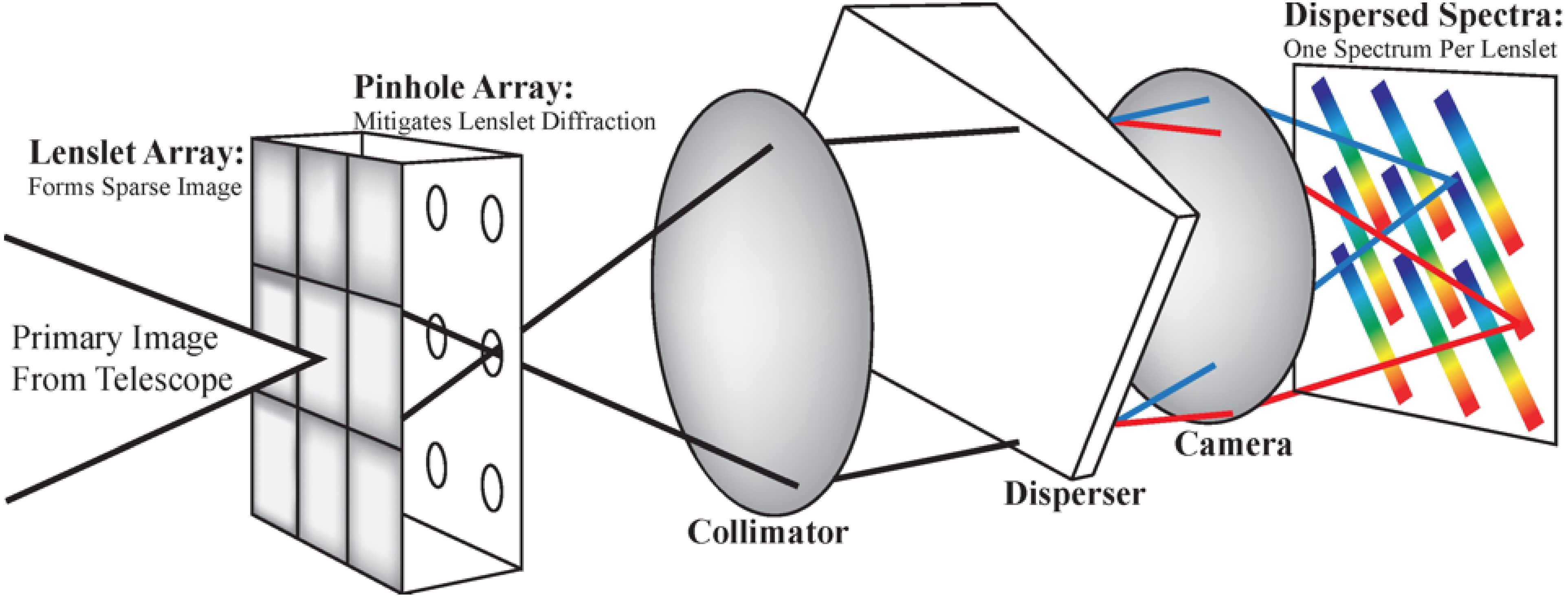
Marois et al.
Nature 2010

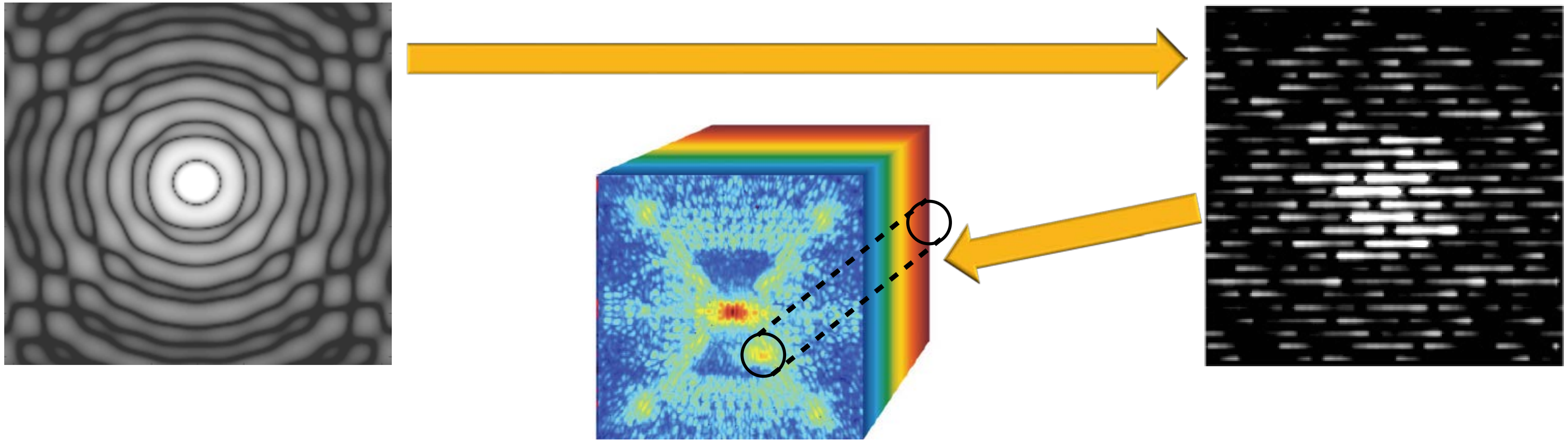


Fomalhaut b: Kalas et al., 2008



Basics (…again for the 3rd or 4th time) of an IFS

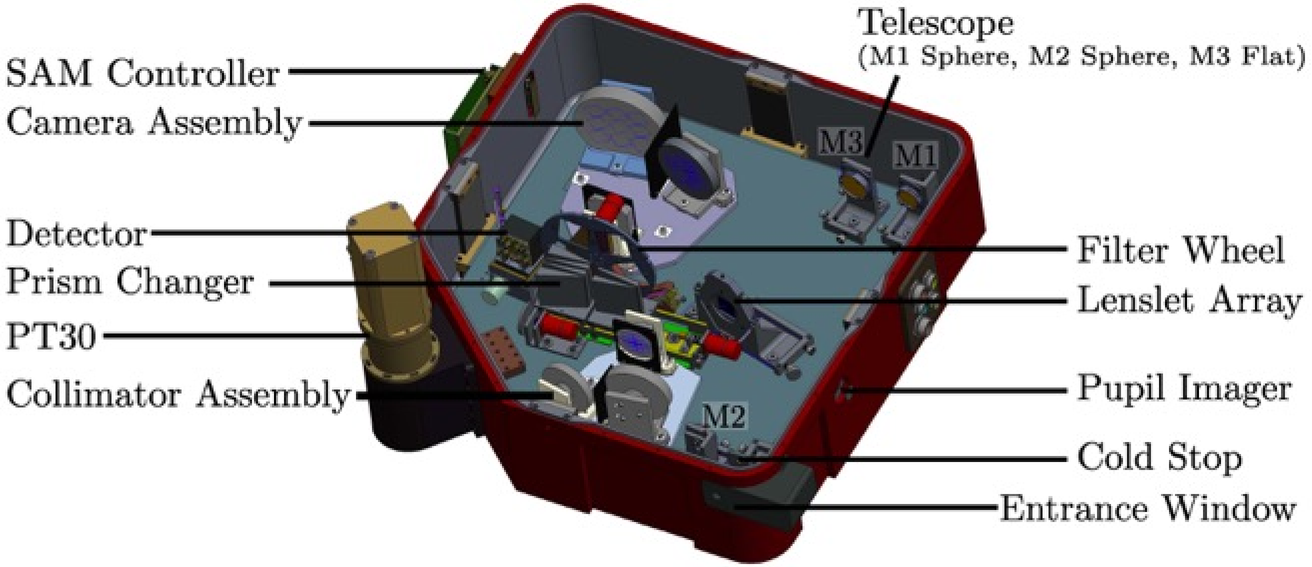




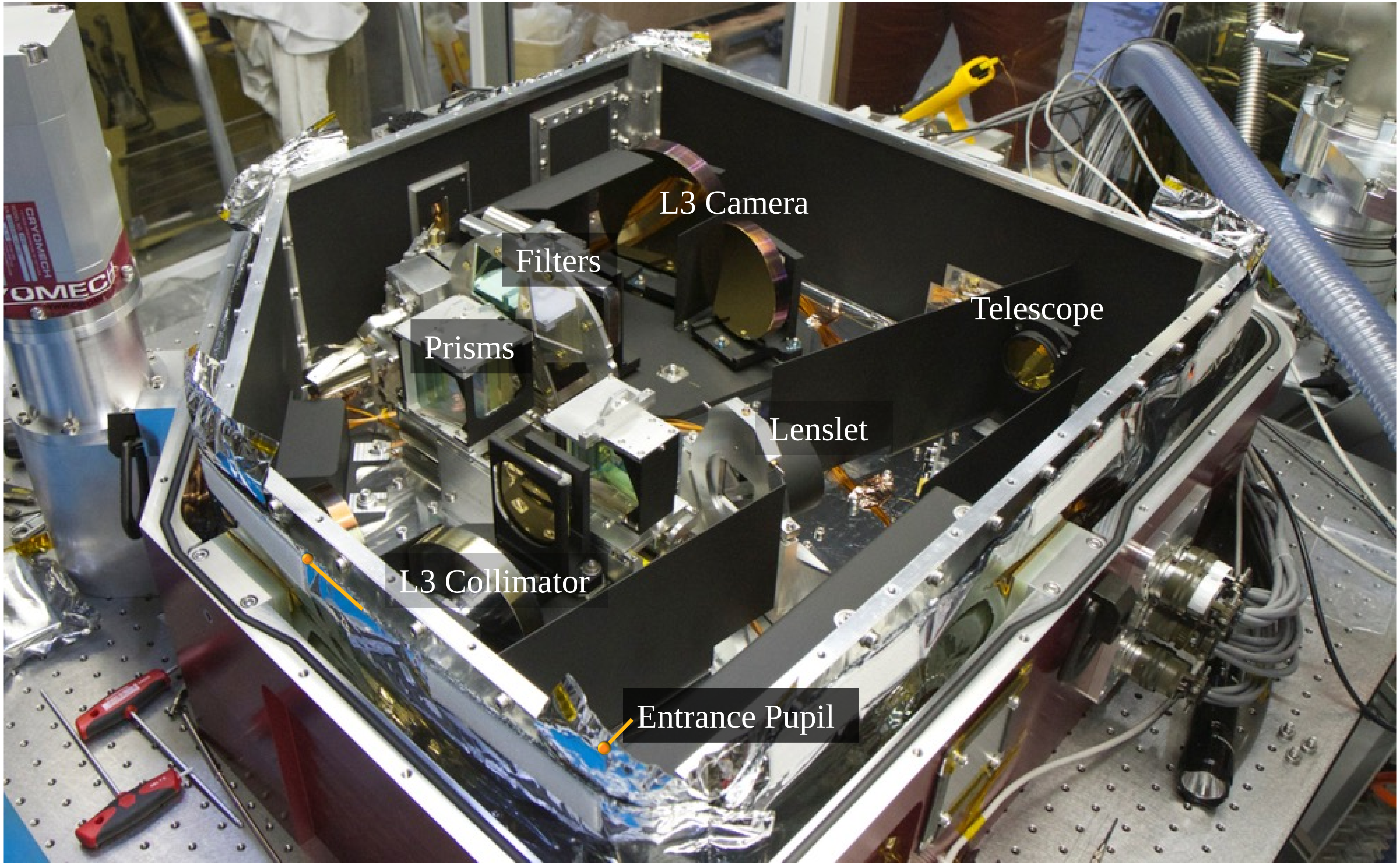
The CHARIS Top Level Design

- Reflective Optics
- Lenslet-based design
- Pinhole Array at Lenslet
    Woodgate et al. 200(
    Bonfield et al. 2008
- F/9 Lenslets and relays
- H2RG detector

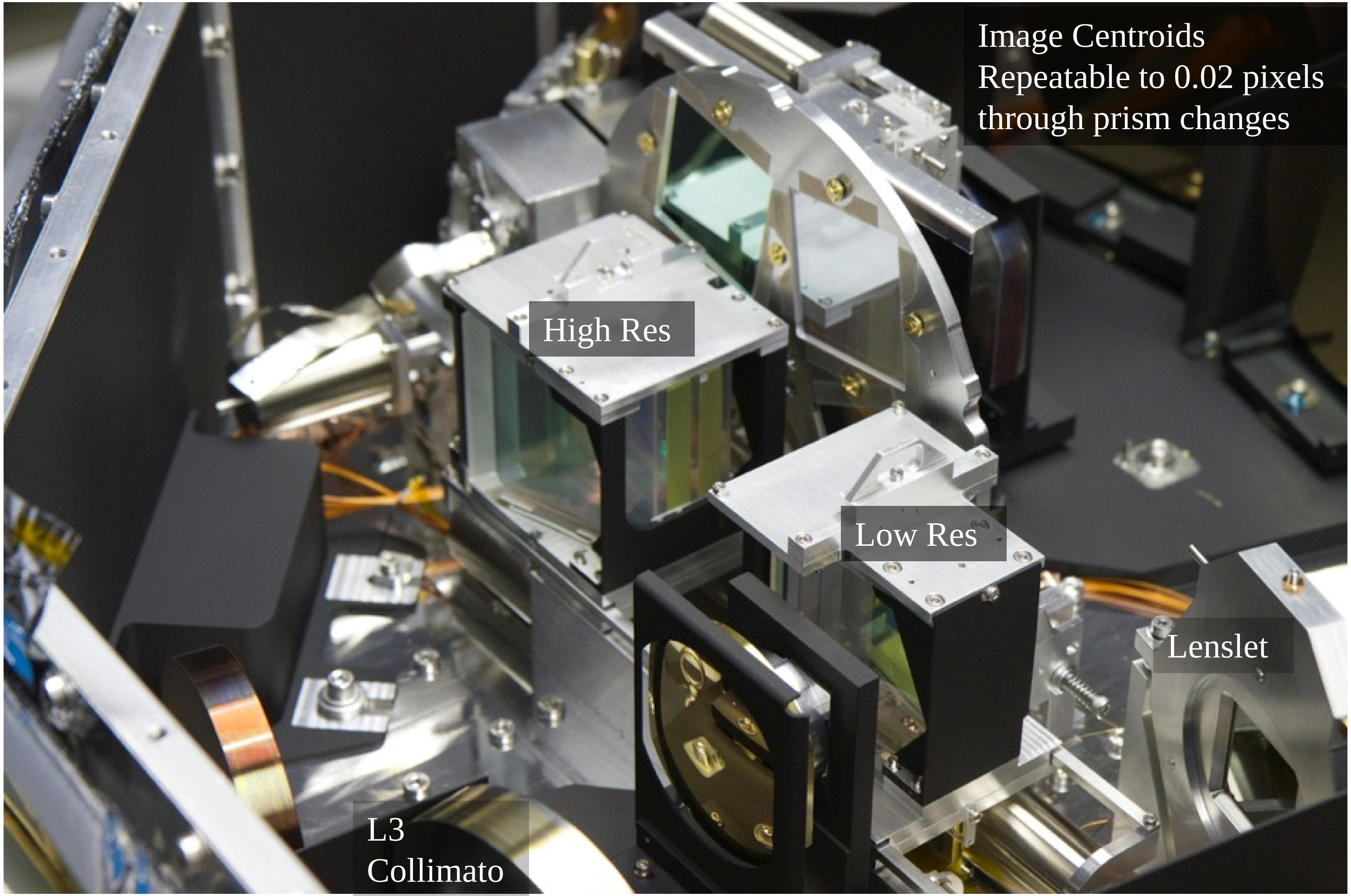
Linux and Windows



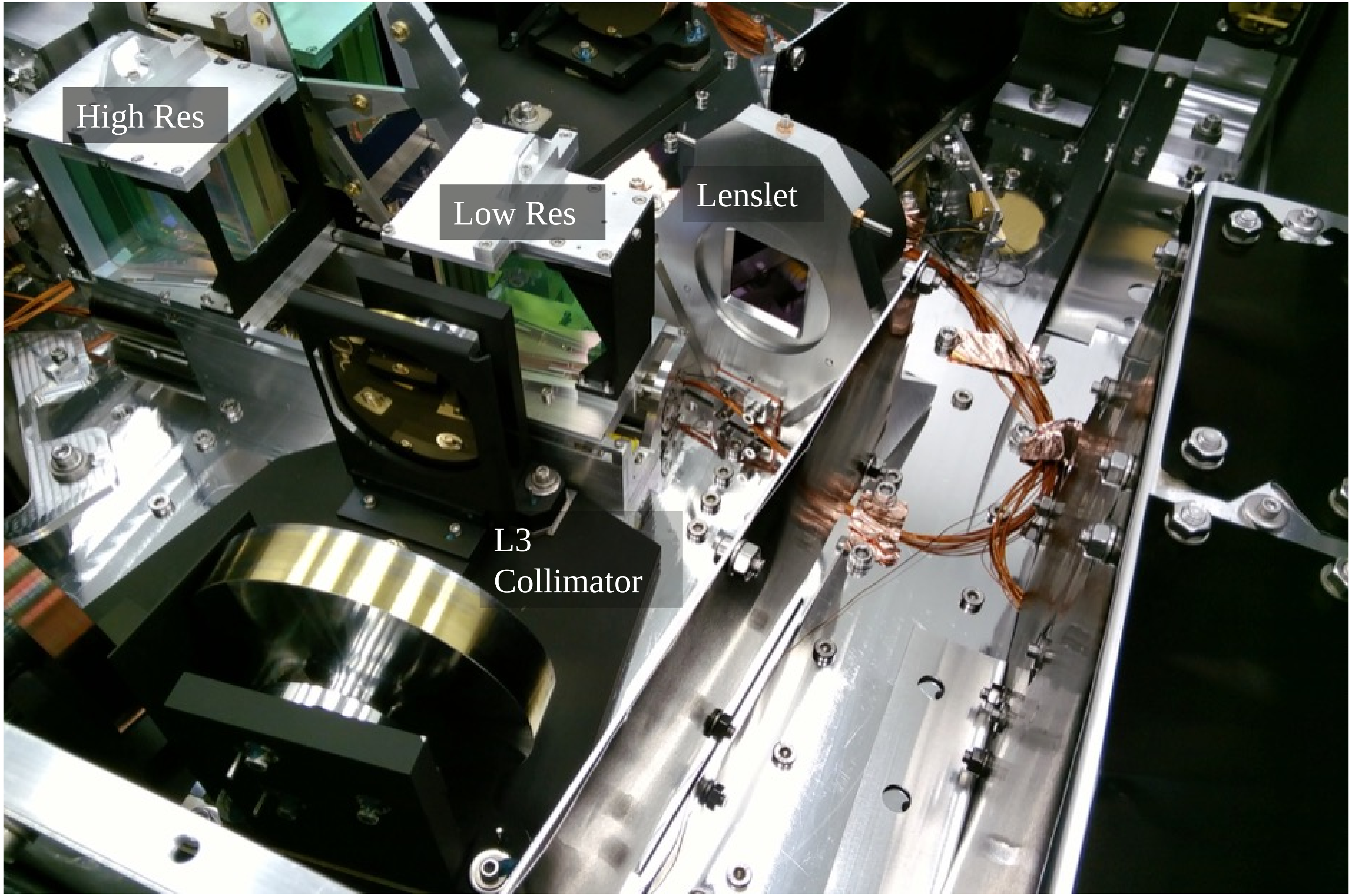
The Final Hardware



Slider Mechanism Locks in Beam

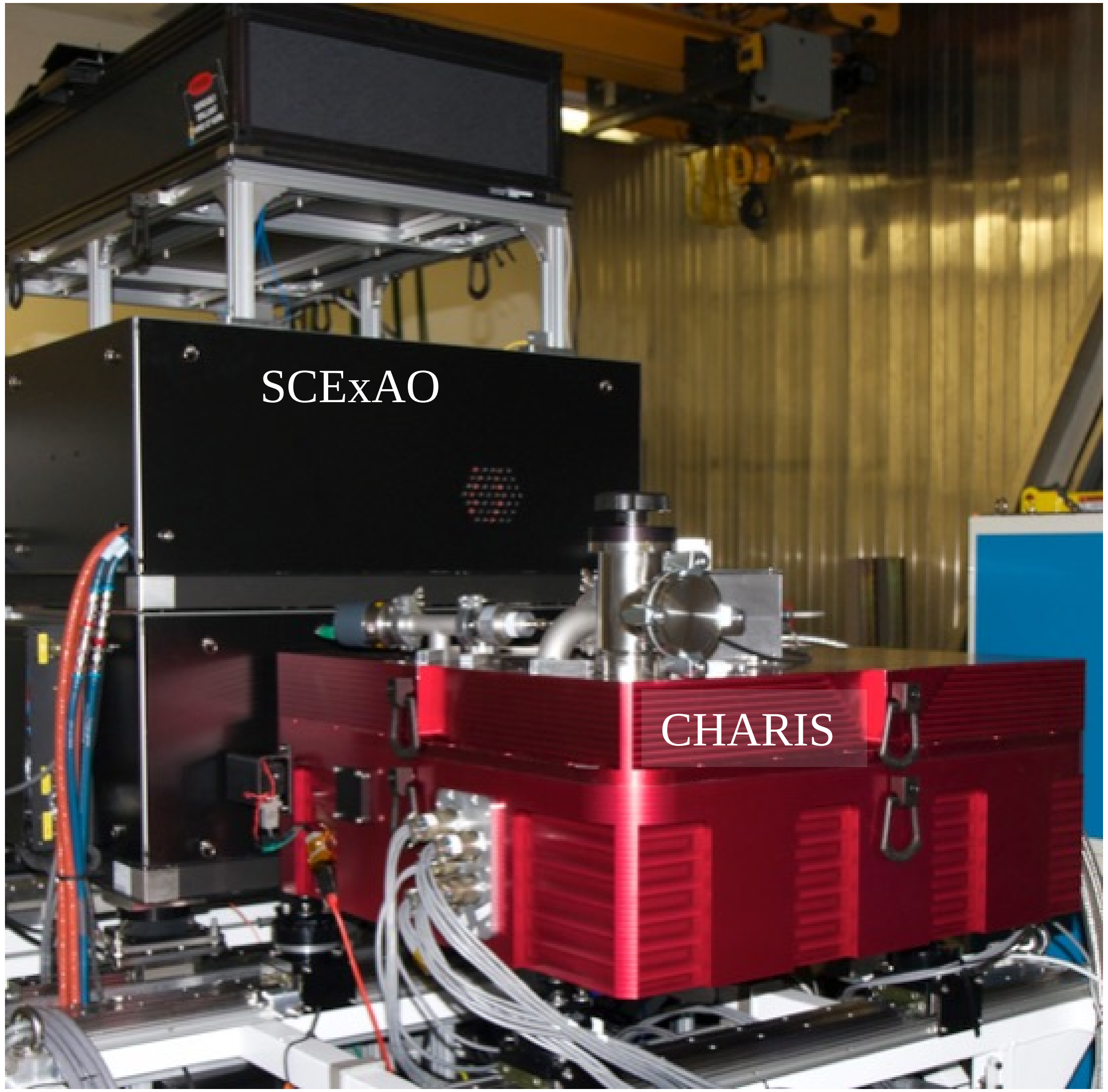


Zoom-in On Key Optics



Top Level Specs

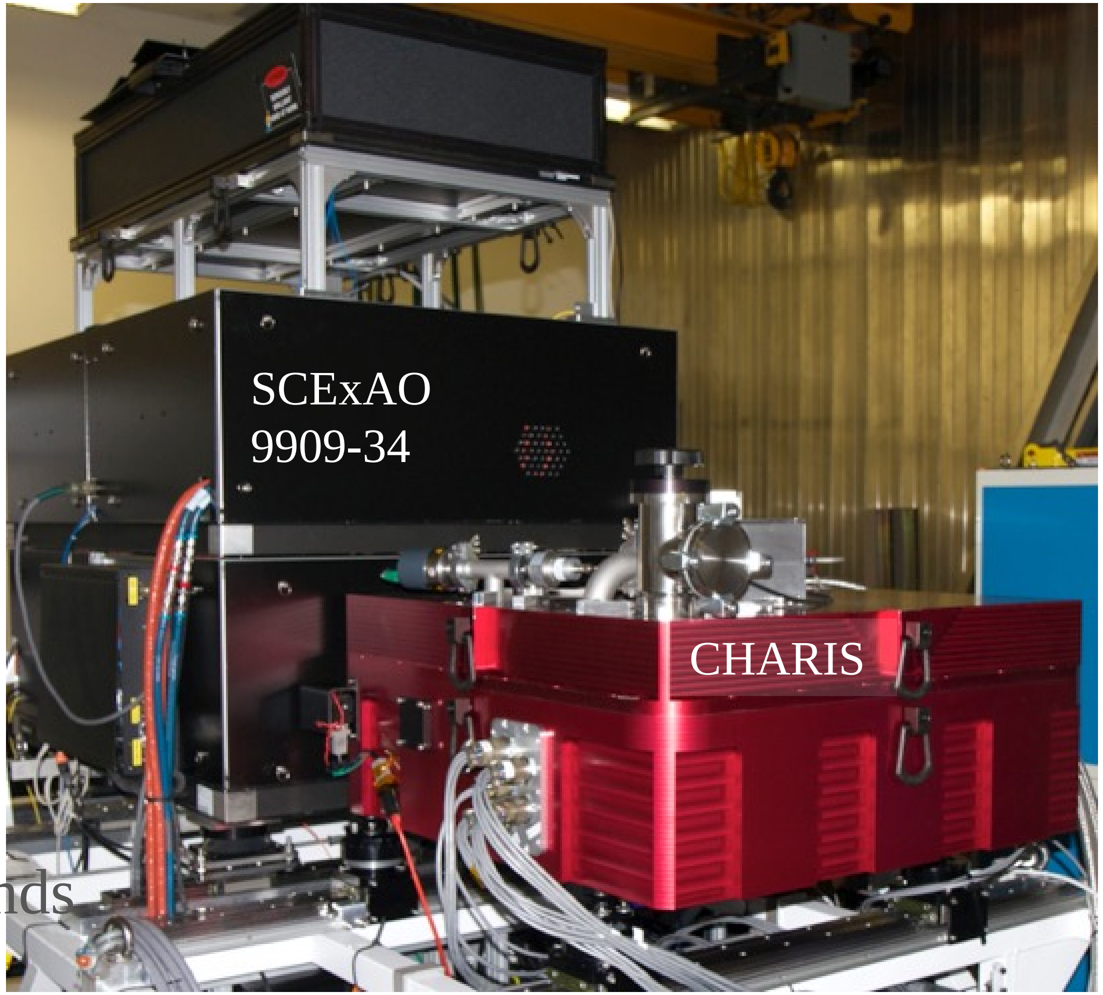
- Major Science Objective:
  - Spectral characterization
    - Exoplanets
    - Disks
    - Brown dwarfs
  - Supports Coronagraph IWA = 3 λ/D = 90 mas
    Current coronagraphs are pushing inside
  - 2.07”x2.07” FOV
  - R~19, J+H+K Band
    - ~53% Throughput
  - R~65-85: J,H, and K Bands
    - ~40% Throughput



CHARIS work was performed under a Grant-in-Aid for Scientific Research on
Innovative Areas from MEXT of the Japanese government (Number 23103002) (Hayashi, Kasdin)

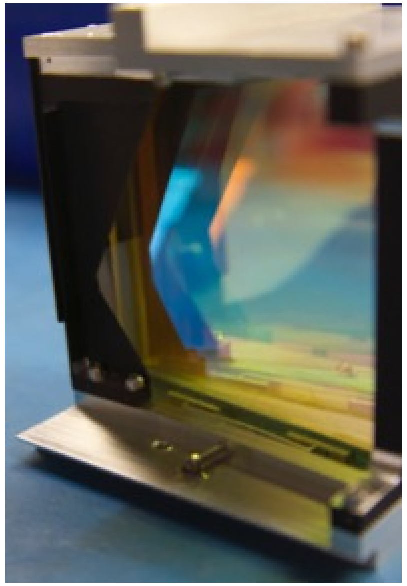
The CHARIS IFS

- Major Science Objective:
  - Spectral characterization
    - Exoplanets
    - Disks
    - Brown dwarfs
  - IWA = 3 λ/D = 90 mas
  - 2.07”x2.07” FOV
  - R~19, J+H+K Band
    - ~53% Throughput
  - R~65-85: J,H, and K Bands
    - ~40% Throughput
  - Technology Contributions: Crosstalk Mitigation, New Dispersion Modes/Materials

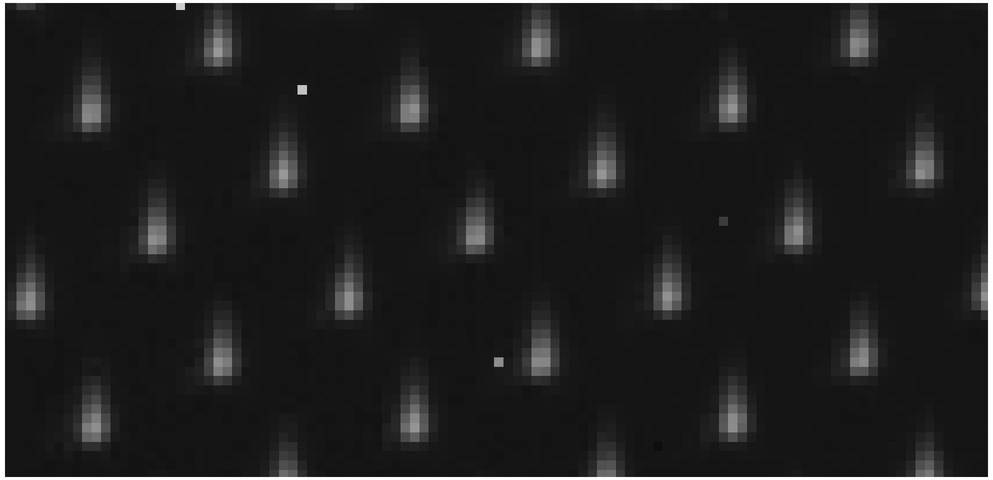


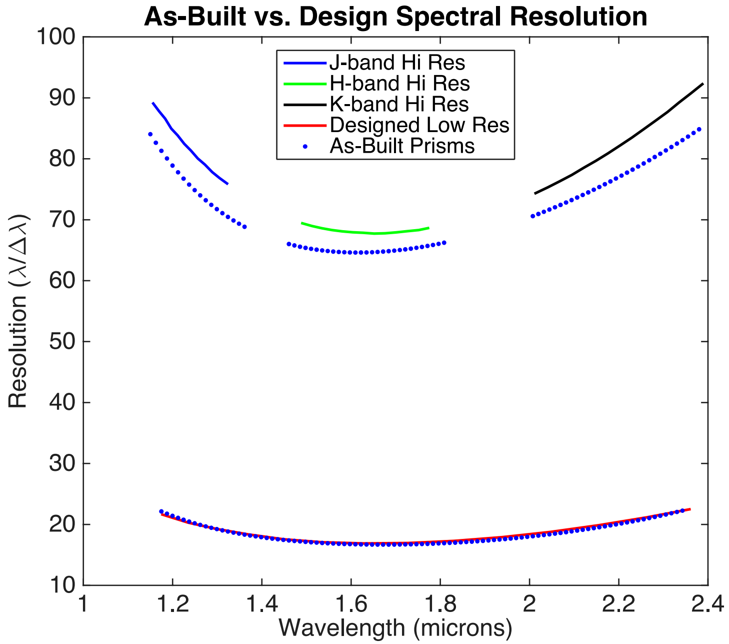
- CHARIS work was performed under a Grant-in-Aid for Scientific Research on Innovative Areas from MEXT of the Japanese government (Number 23103002) (Hayashi, Kasdin)
- PISCES work was performed under the Nancy Grace Roman Technology Fellowship (McElwain)

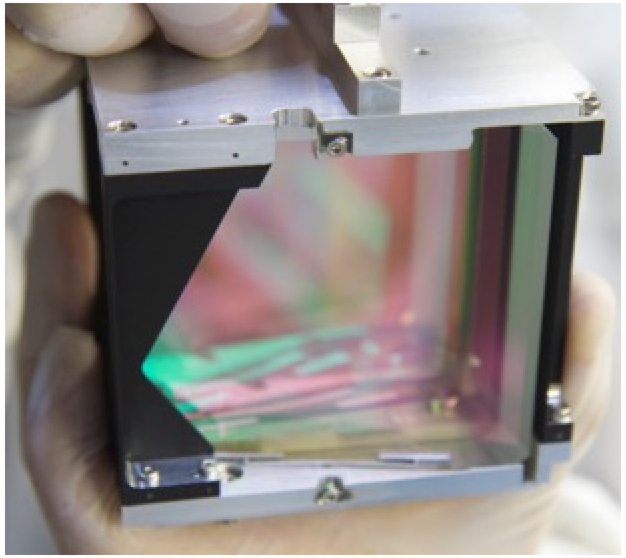
Low vs. High Resolution Mode: Thermal Background



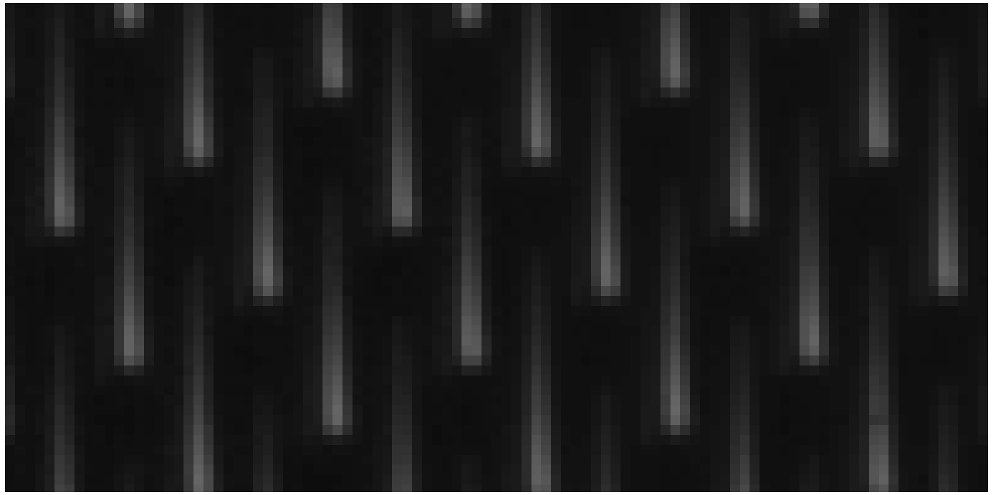
Low Resolution

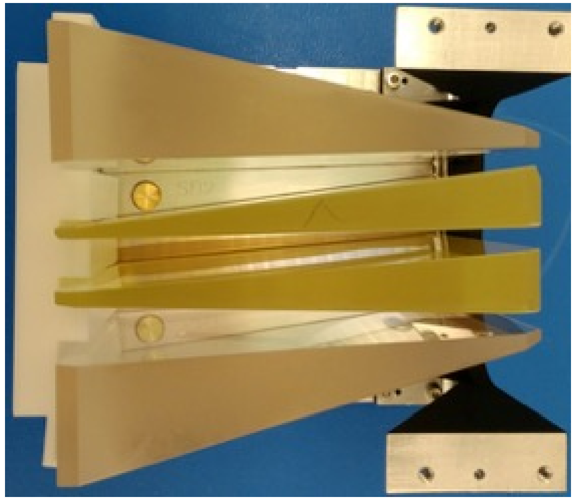






K-band





Last Year: First Alignment to SCExAO

Pupil Alignment

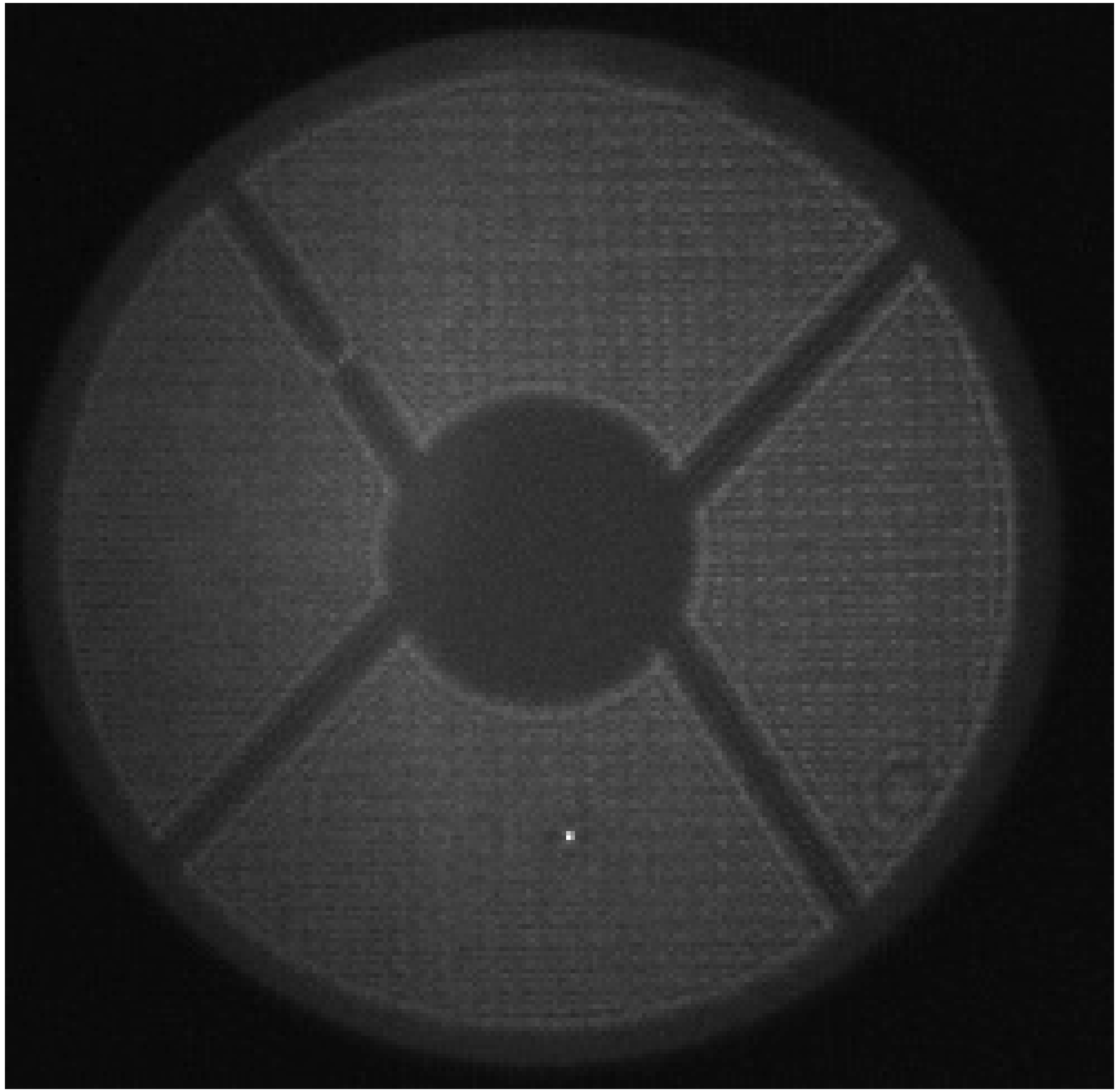
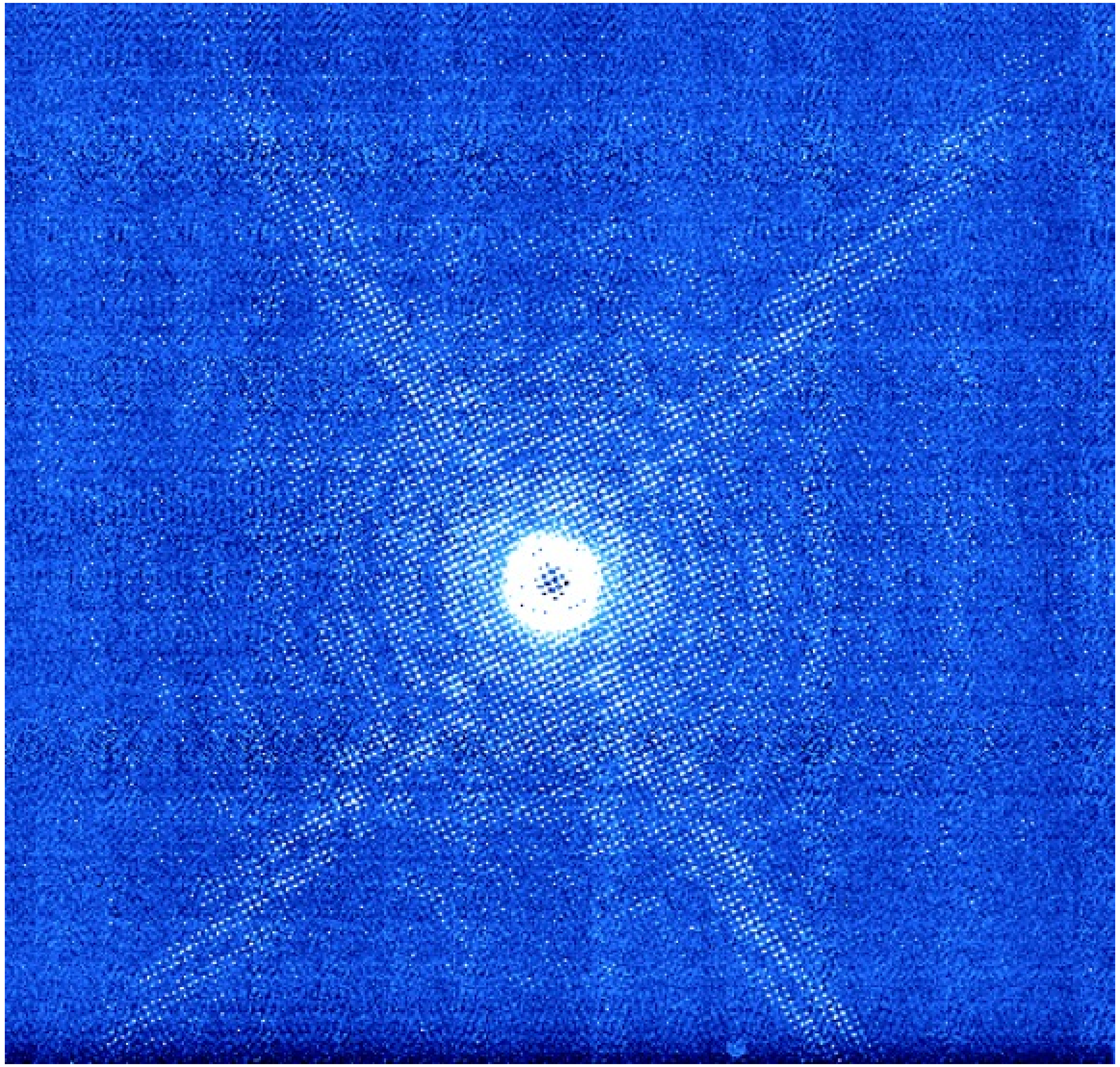
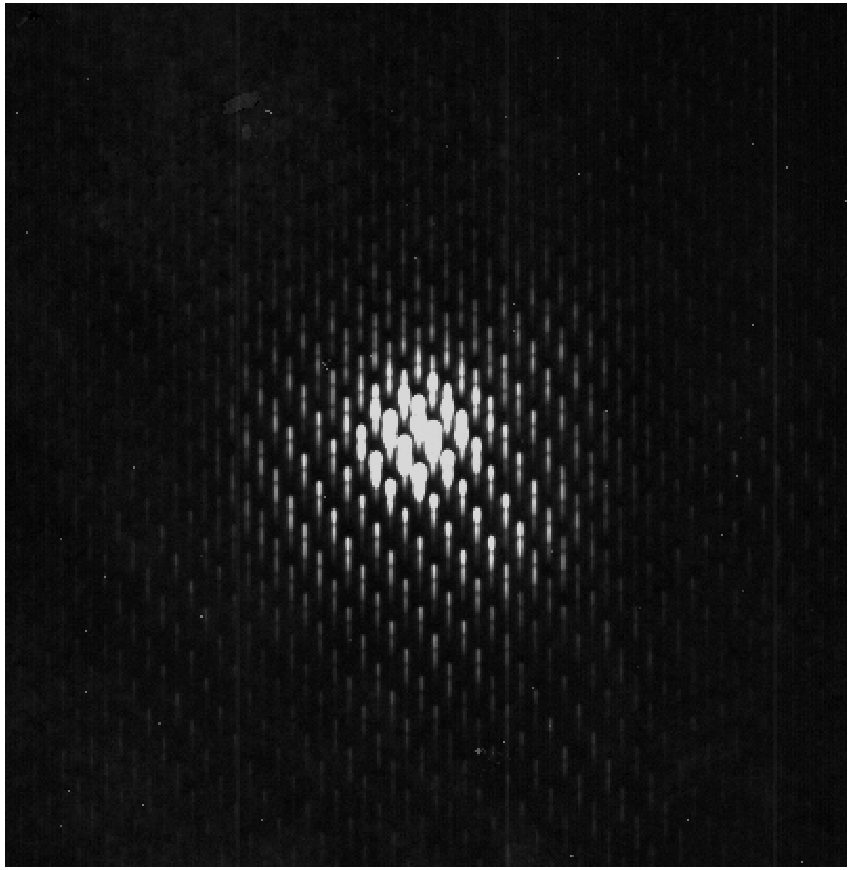


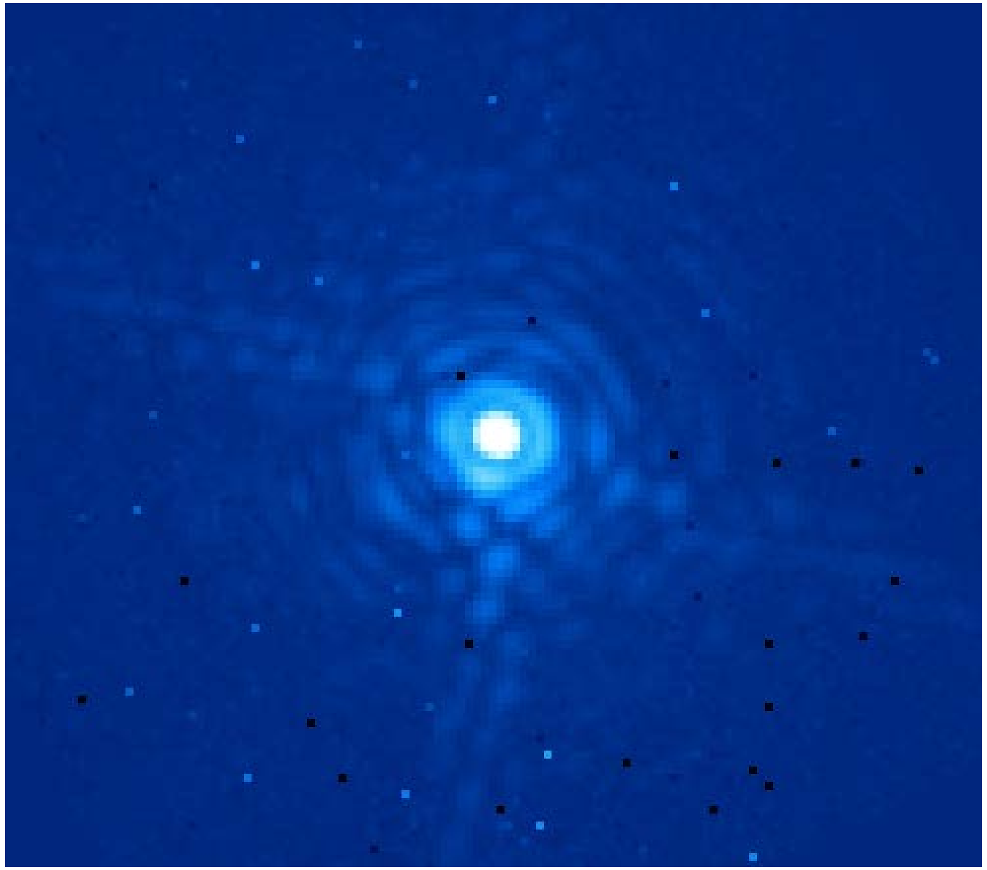
Image Alignment



~1 Week After SPIE 2016!



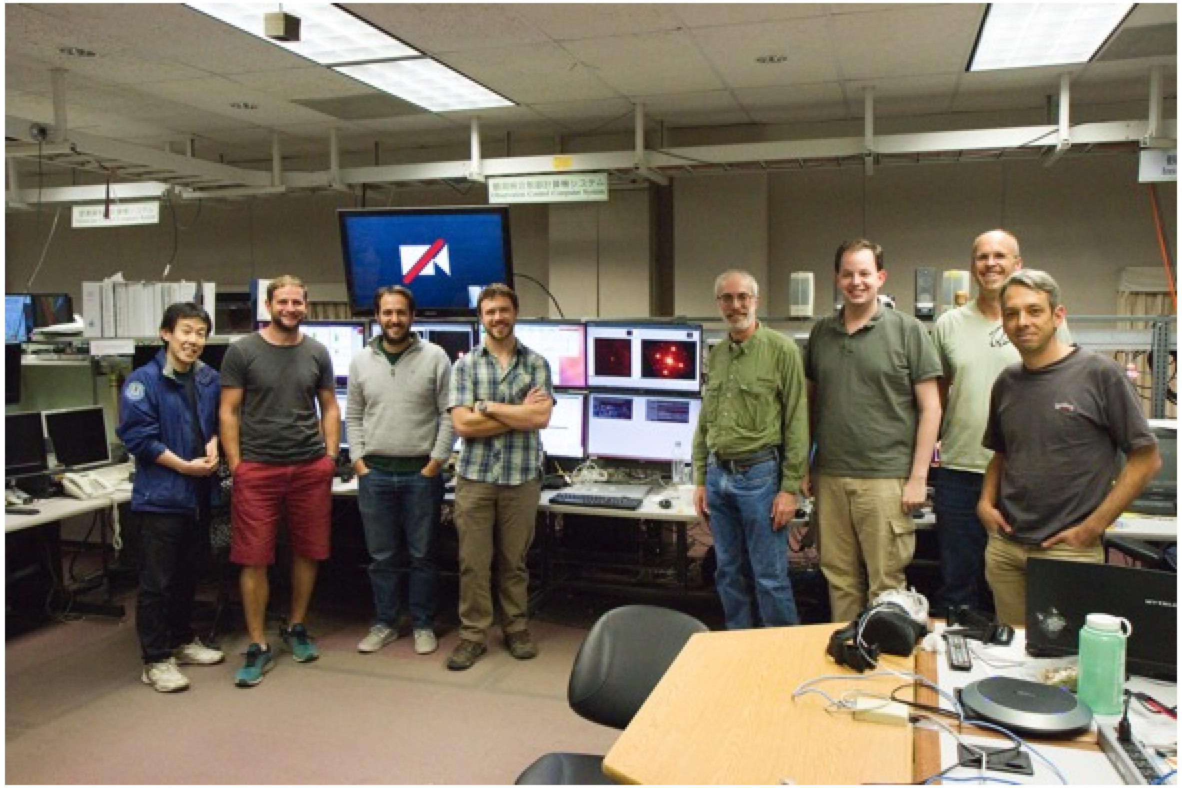
First Light On Detector



Extracted Image at ~1550

CHARIS Commissioning Tasks

- Measure CHARIS wavelength calibration
- Determine throughput & zero point
- Measure CHARIS Contrast
- Photometric Calibration
- DM Spot calibration
- Twilight Flats
- Low Resoluton operation verification & testing
- High Resolution operation verification & testing
- Circumstellar disk demonstration
- Extended object demonstration
- GPI / CHARIS cross calibration objects
- Astrometric Measurements & Plate Scale

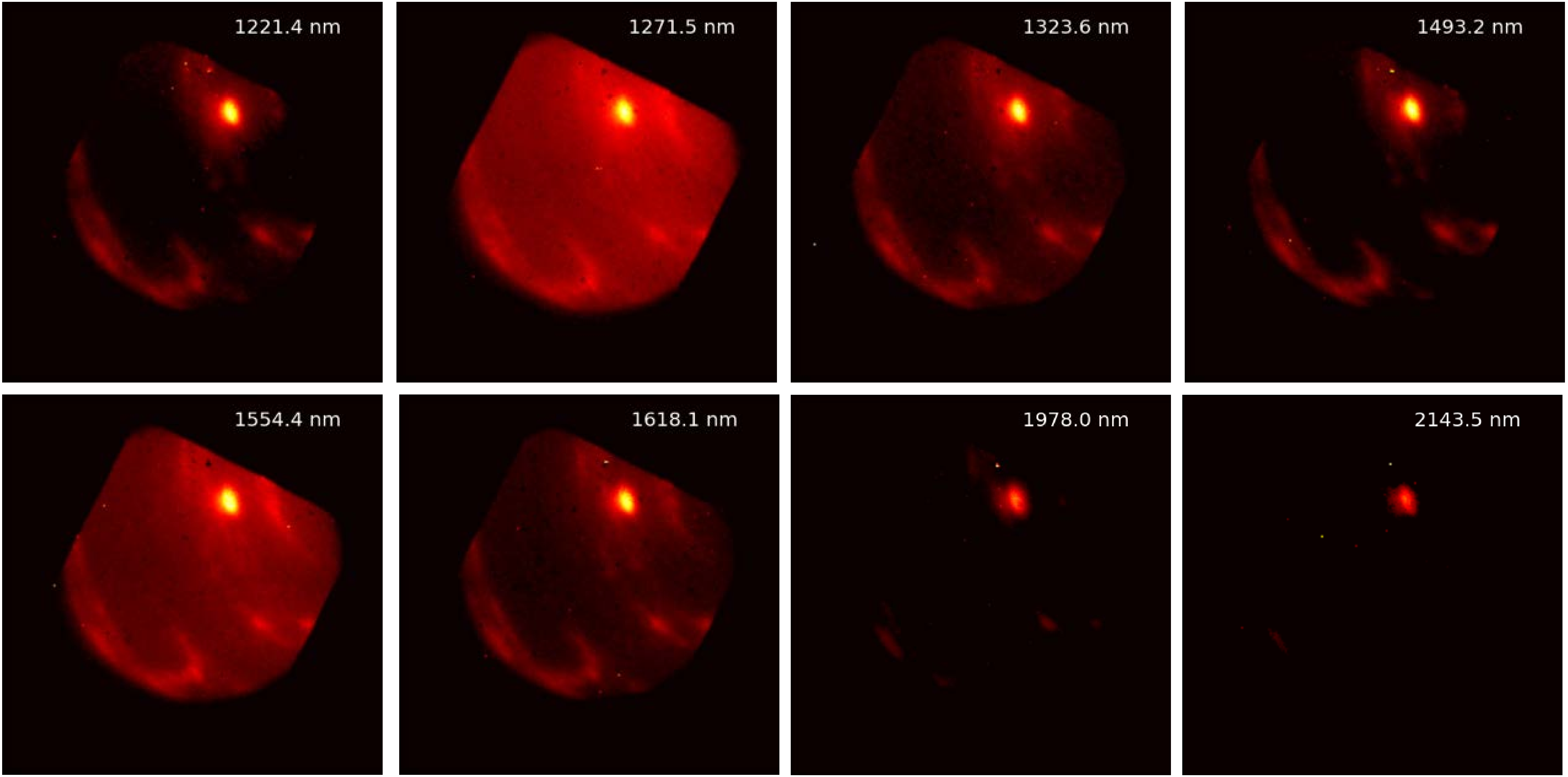


Brown Dwarf HD 1160

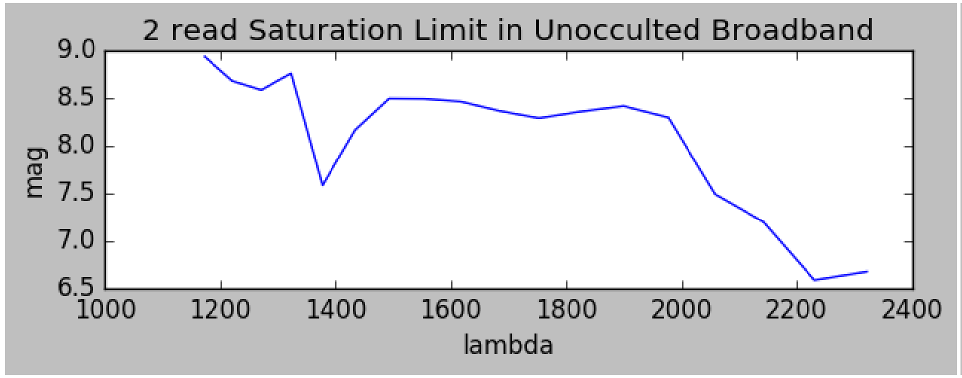
- DM Satellites
  - Astrometric Calibration
  - Photometric Calibration
- Occulted Star
- Brown Dwarf

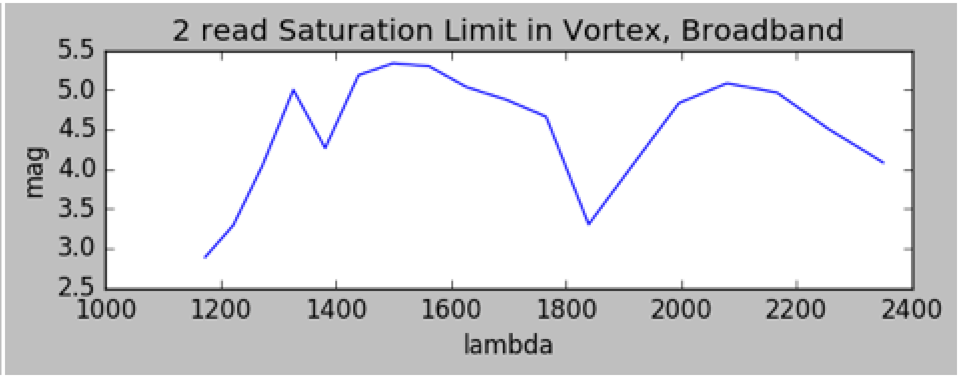
Broadband data by Jeff Chilcote and Tyler Groff
Pretty GIF made by Tim BRandt

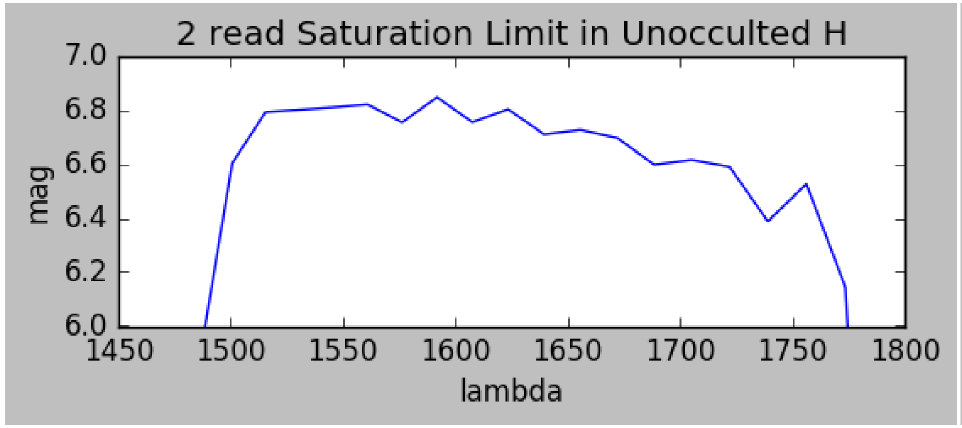
Neptune Broadband Mode – 60 second Exposure

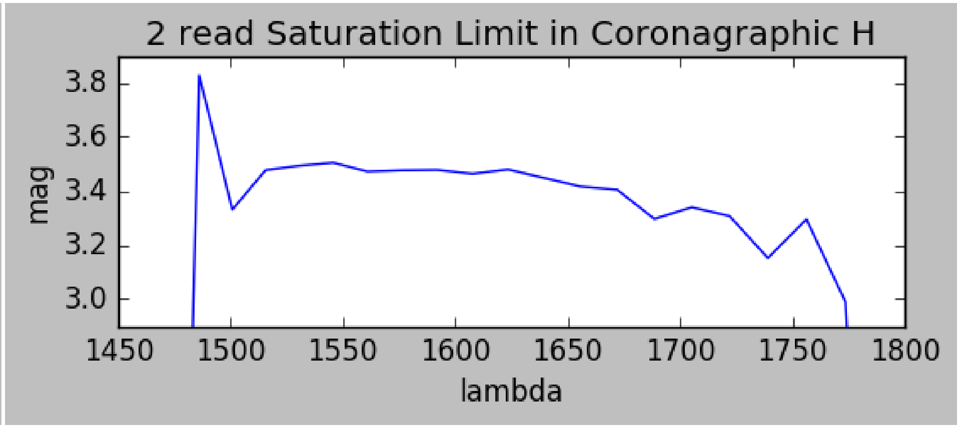


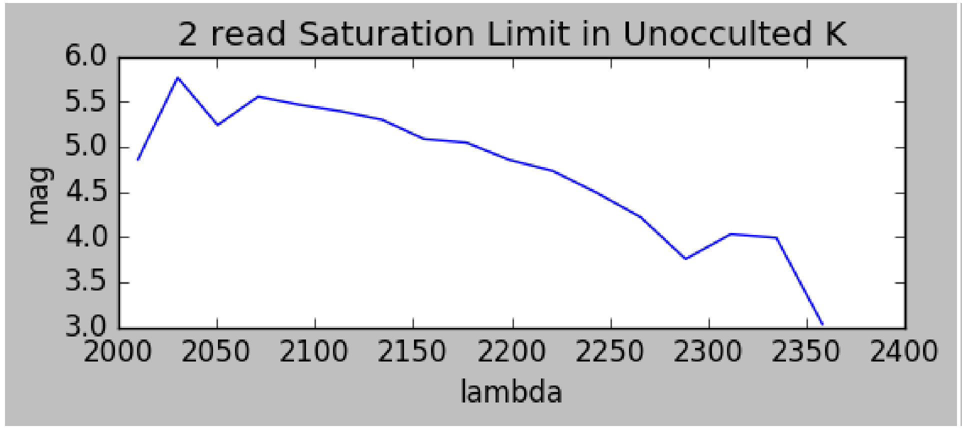
Sensitivity

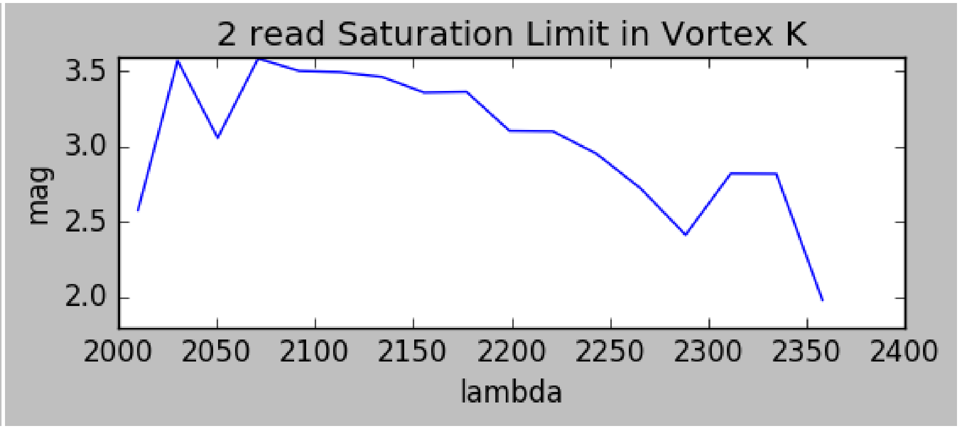






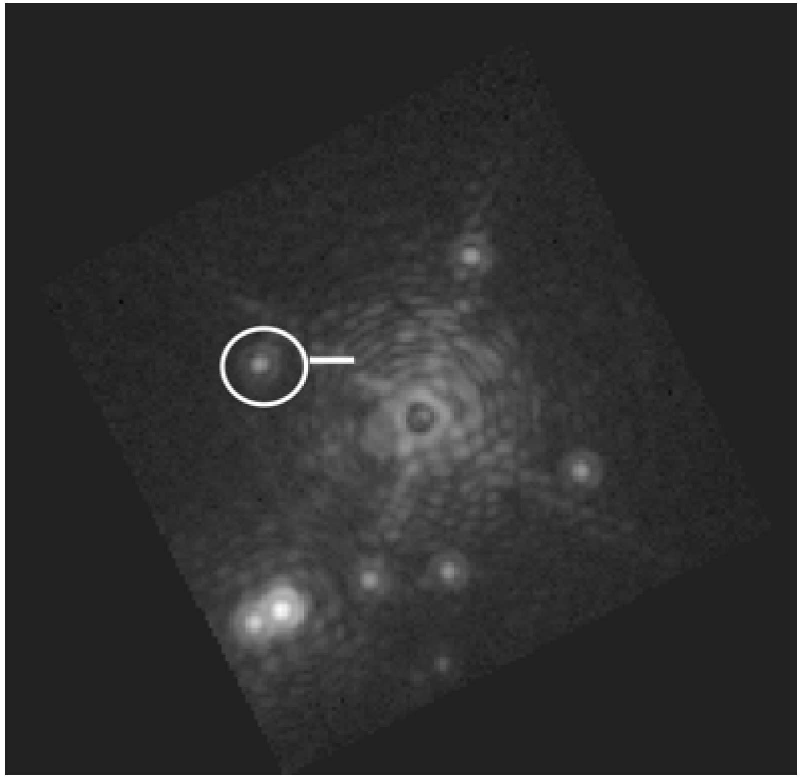






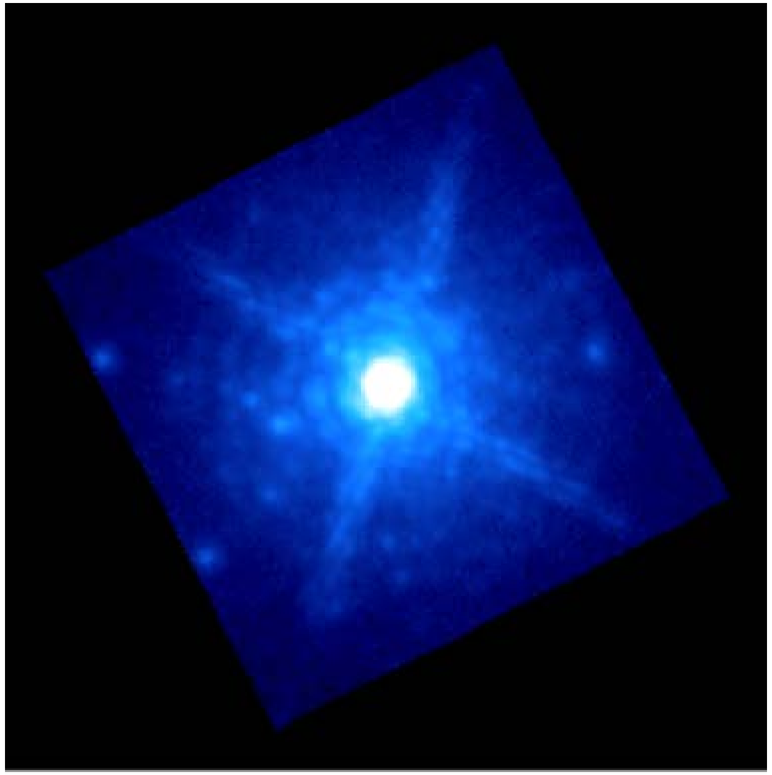
Astrometric Calibrators

Trapezium



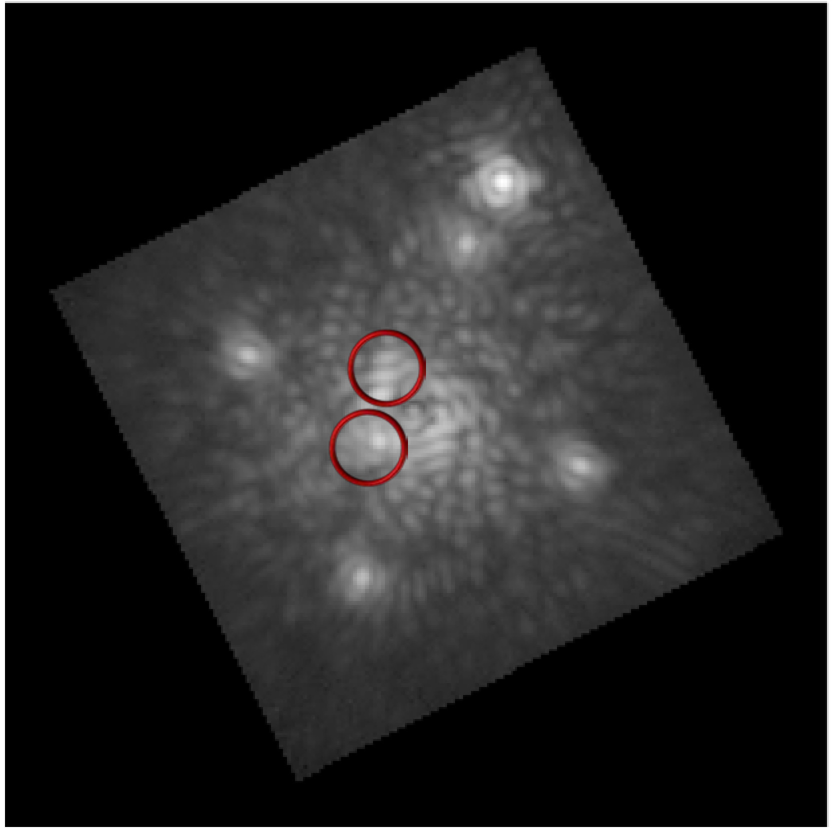
- Astrometric Calibrator
- GPI Cross Calibrator

M5 Globular Cluster

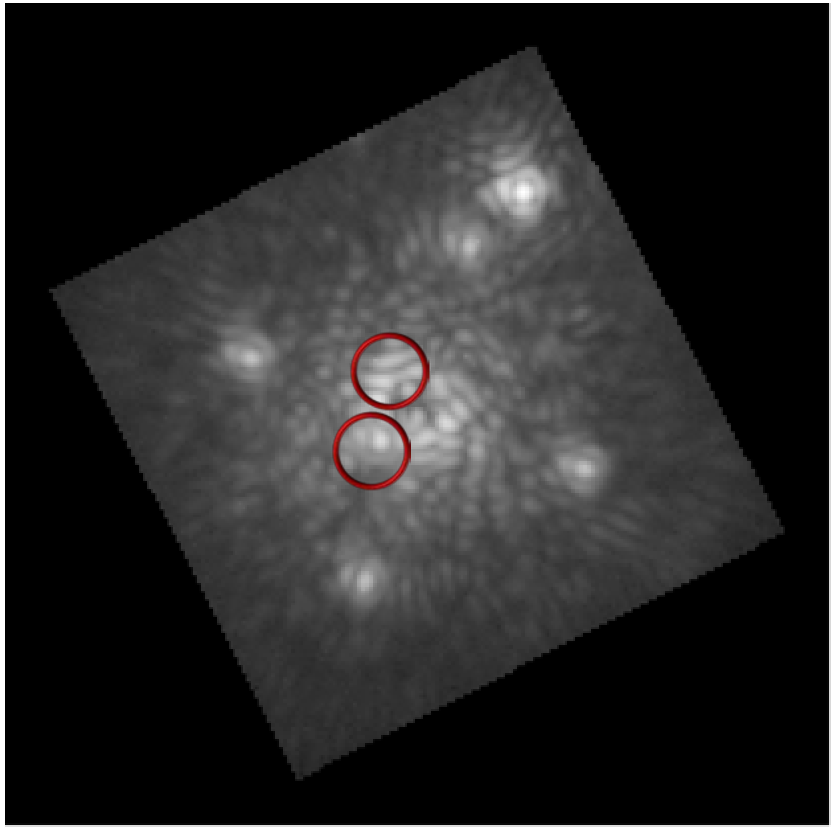


- Astrometric Calibrator
- Plate Scale & Distortion

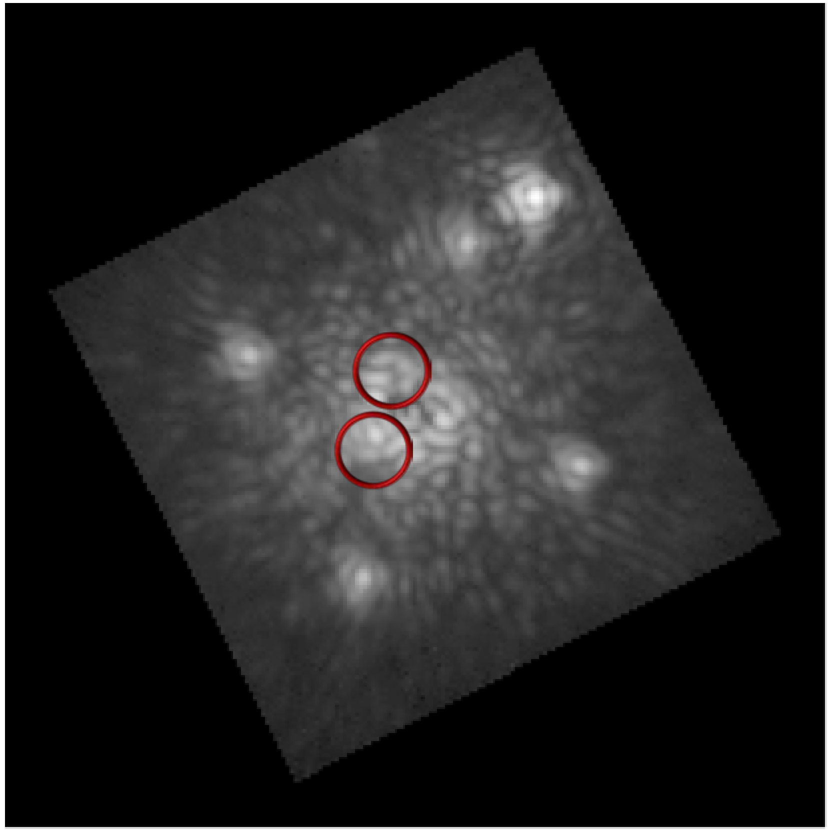
Characteristic CHARIS Data



Start

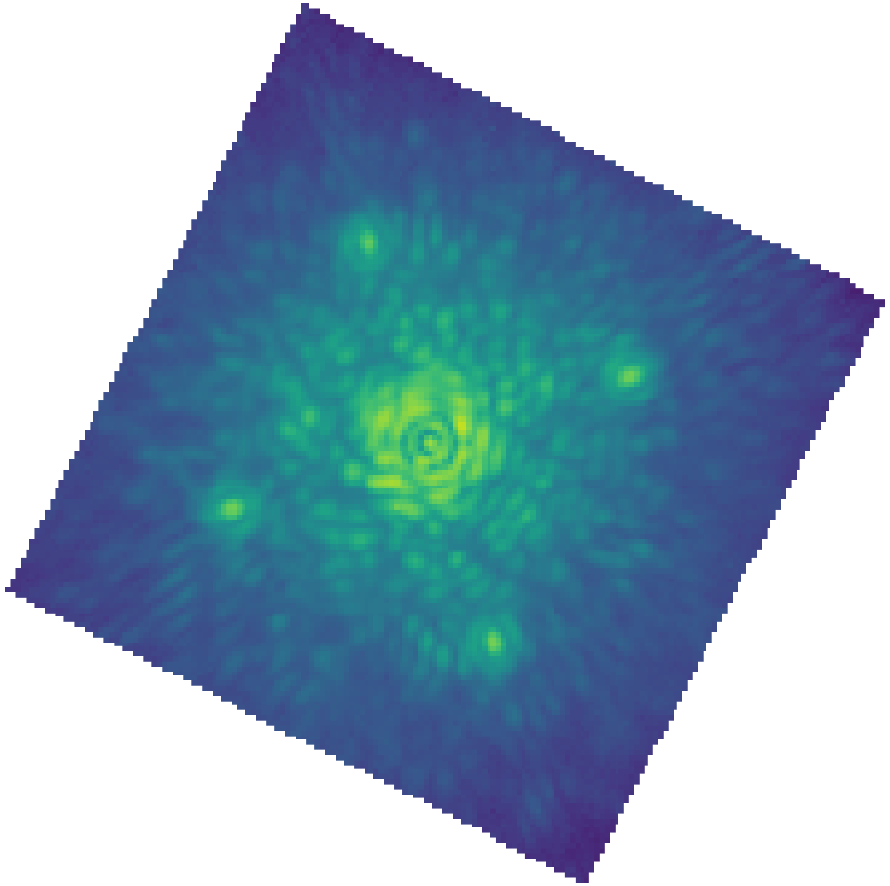


10 min

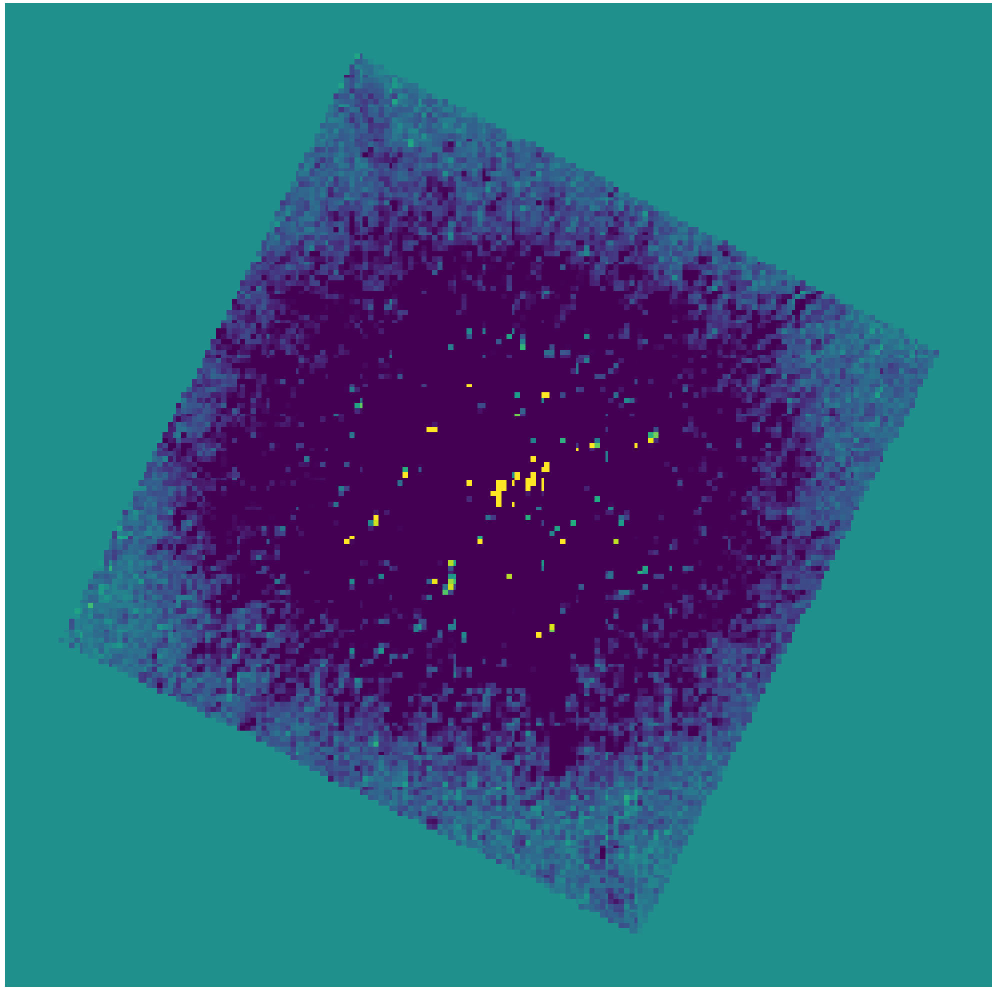


20 min

51 Eri observations

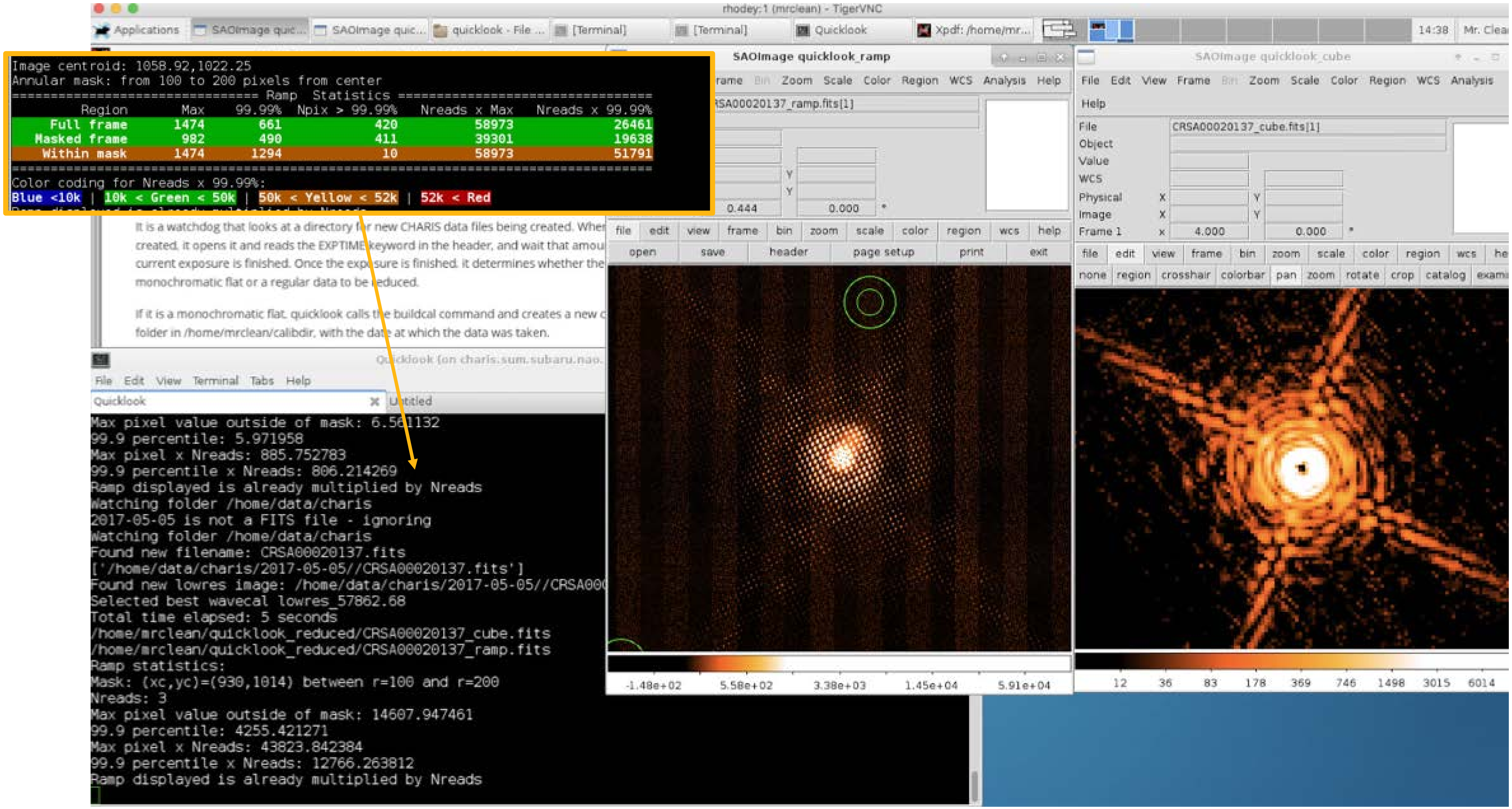


2 hour time series

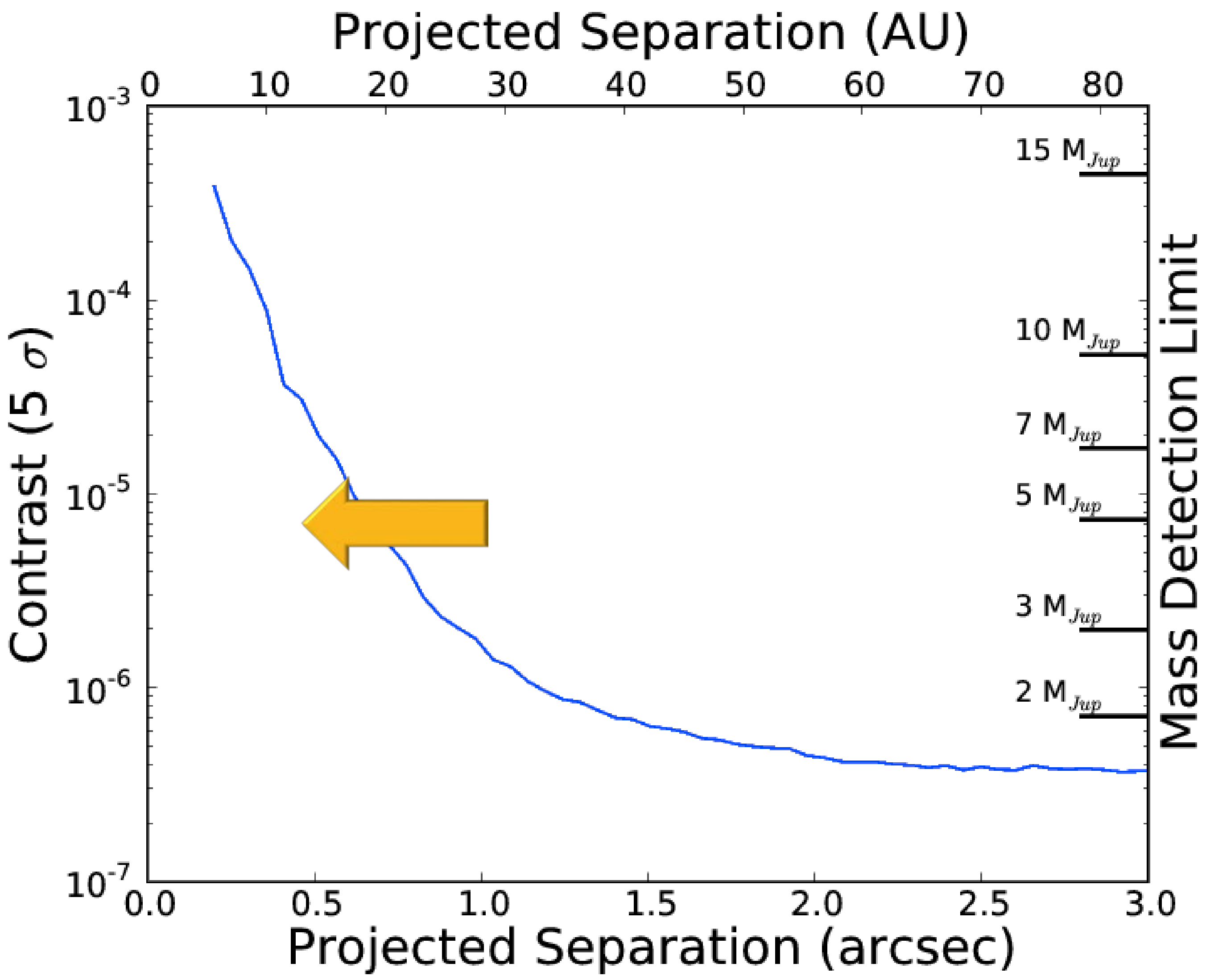


Mean subtracted residual

The Quicklook: A Crisp Look At The Data at the Summit

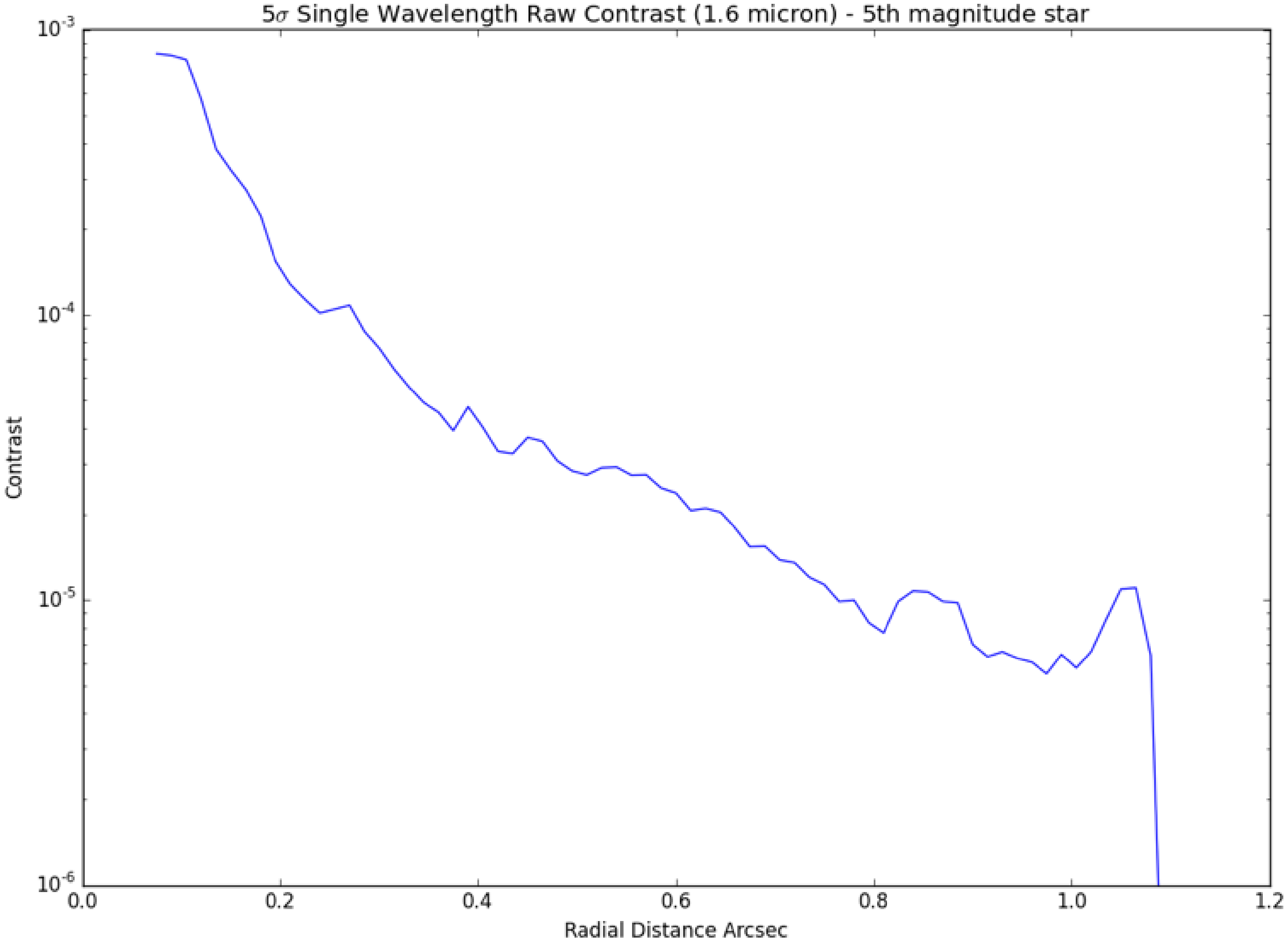


SEEDS Contrast and Goals with CHARIS



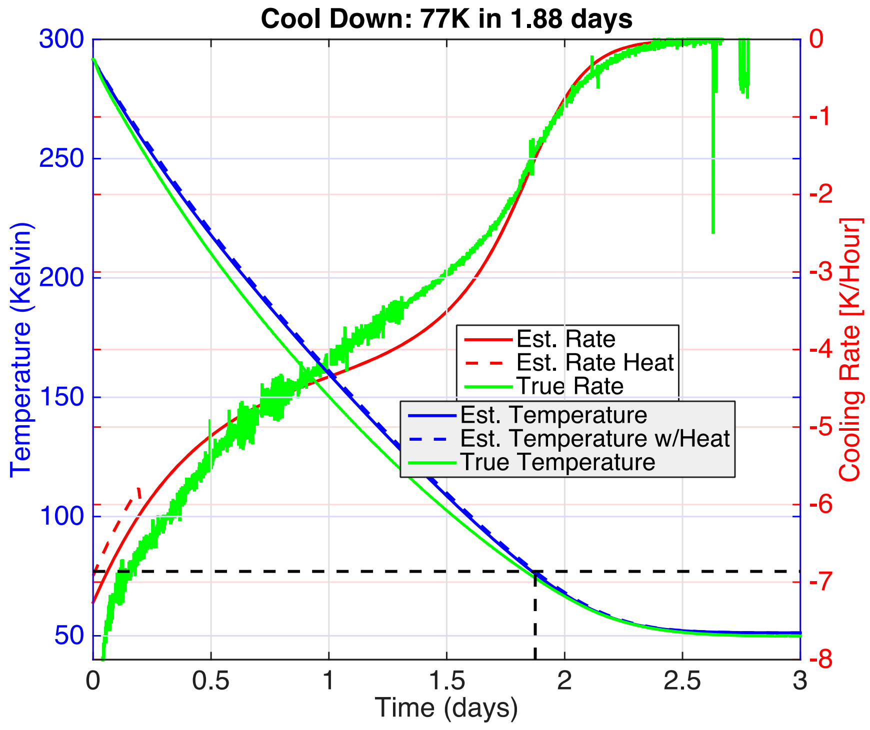
SEEDS Contrast Estimate Courtesy Michael McElwain and Tim Brandt and SEEDS team

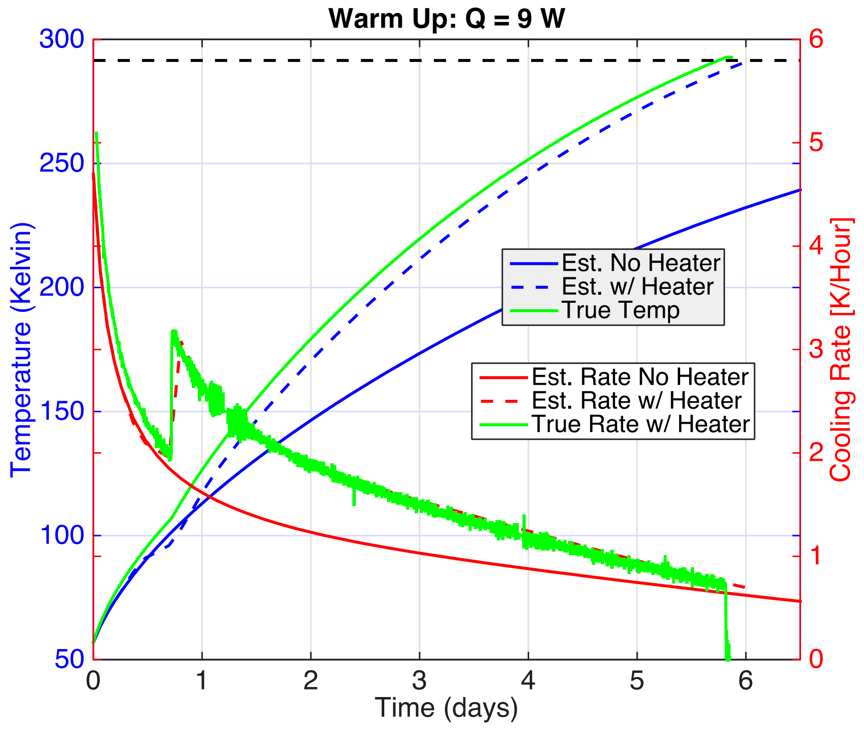
~First Light Contrast Curve



Thermal Performance

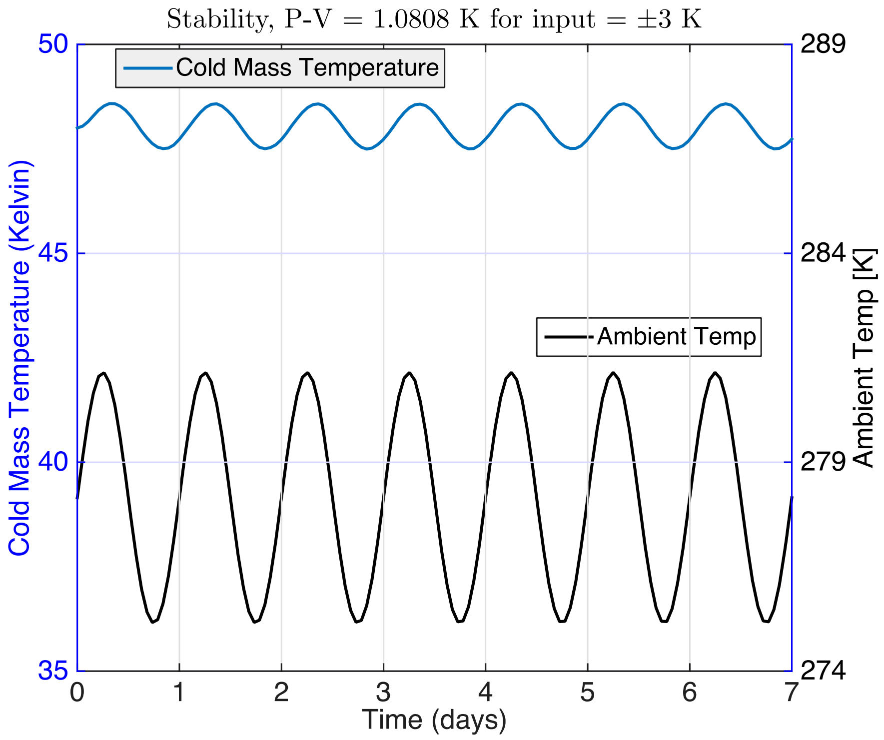
- CHARIS MLI+Cooler performance far exceeds requirement of <80K
  - This likely accounts for some of the dispersion discrepancy in the imaging modes
  - ~13W of load at 50K in a 291.5K ambient environment

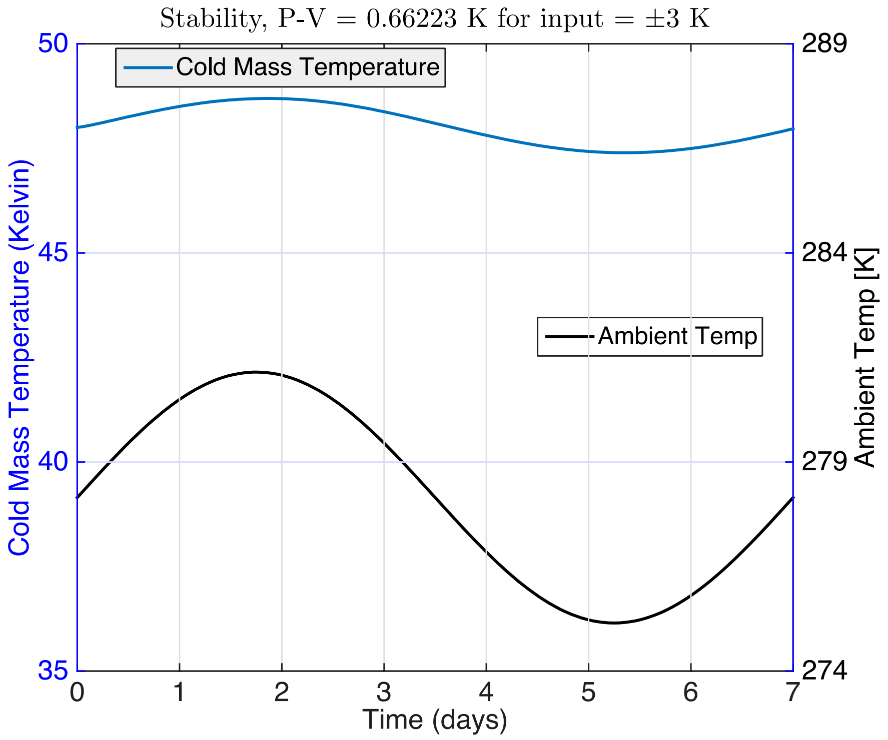




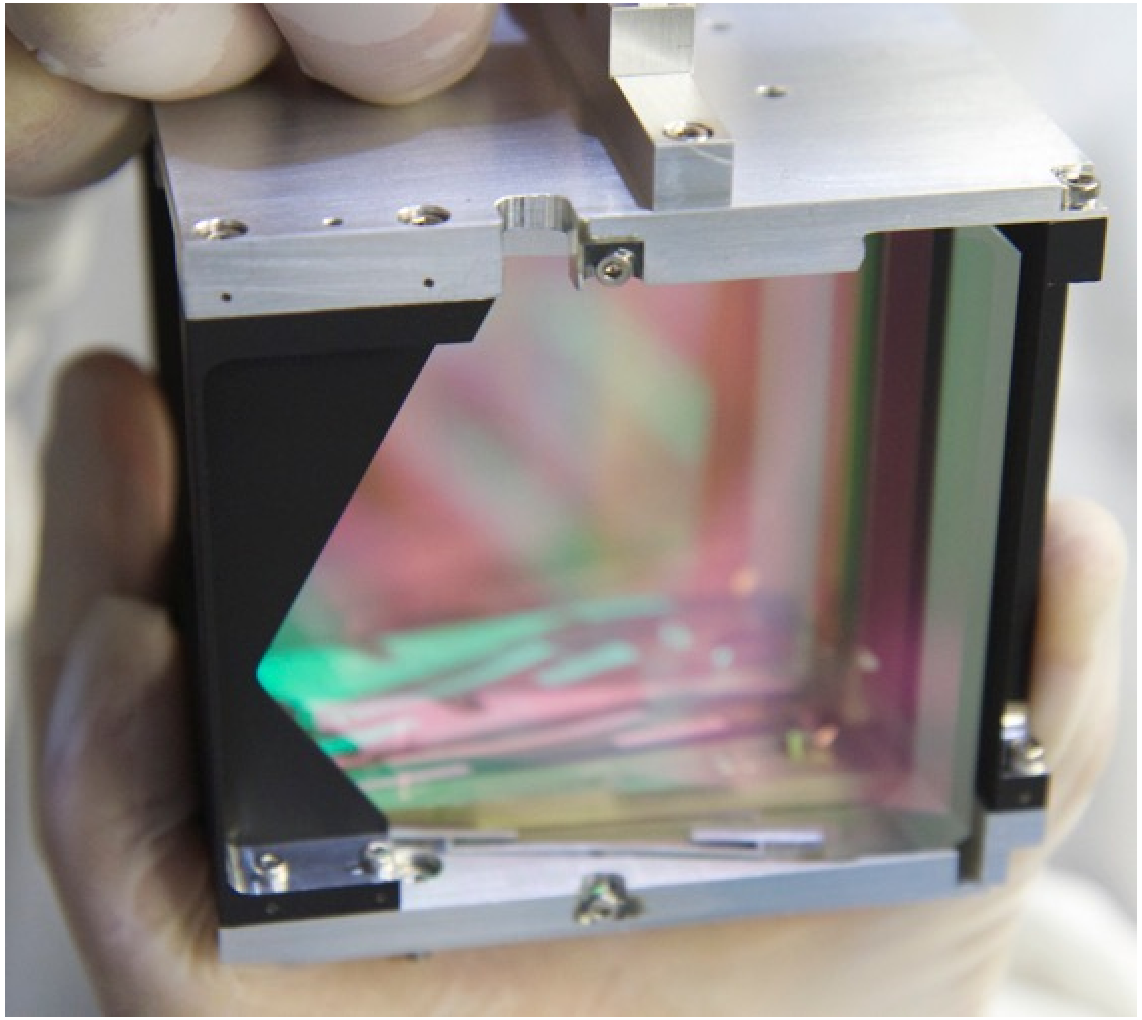
Thermal Stability

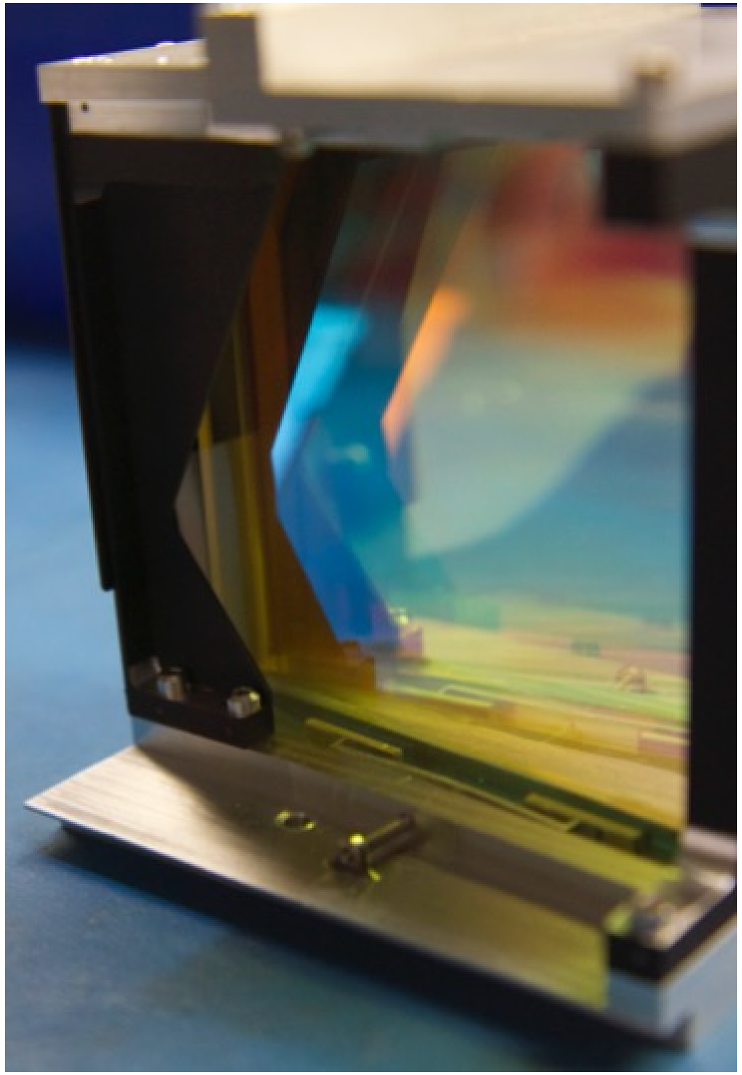
- For an IFS, stability is critical to performance
- Spectra begin to drift on detector with differential expansion



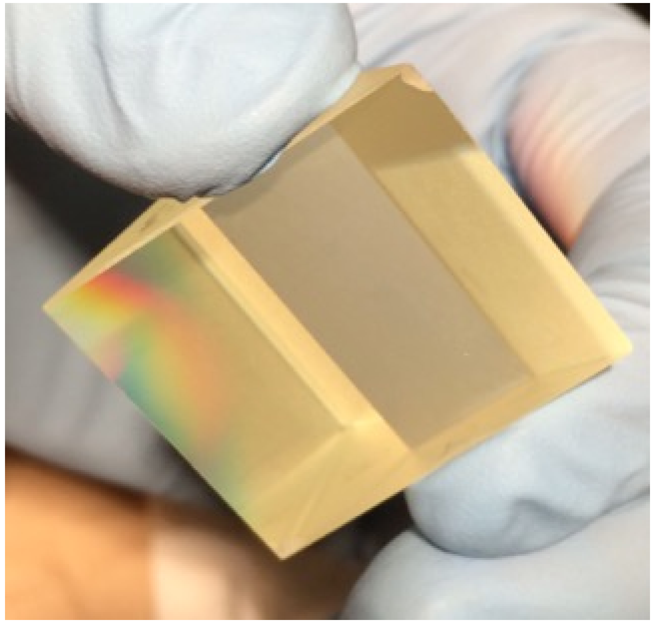


CHARIS Prism Assemblies



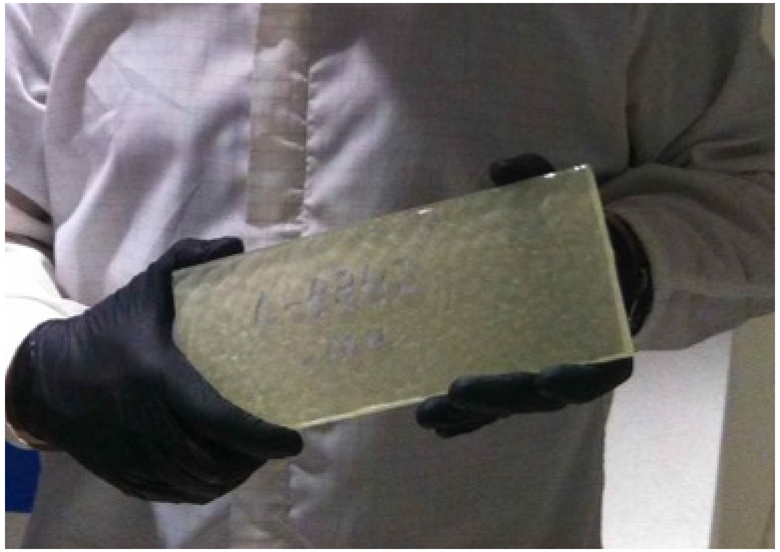


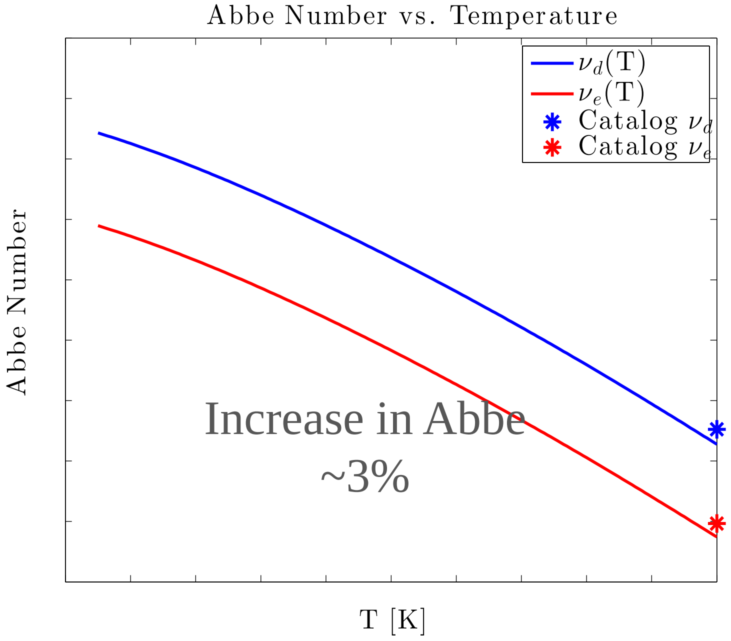
L-BBH2 Material Tests



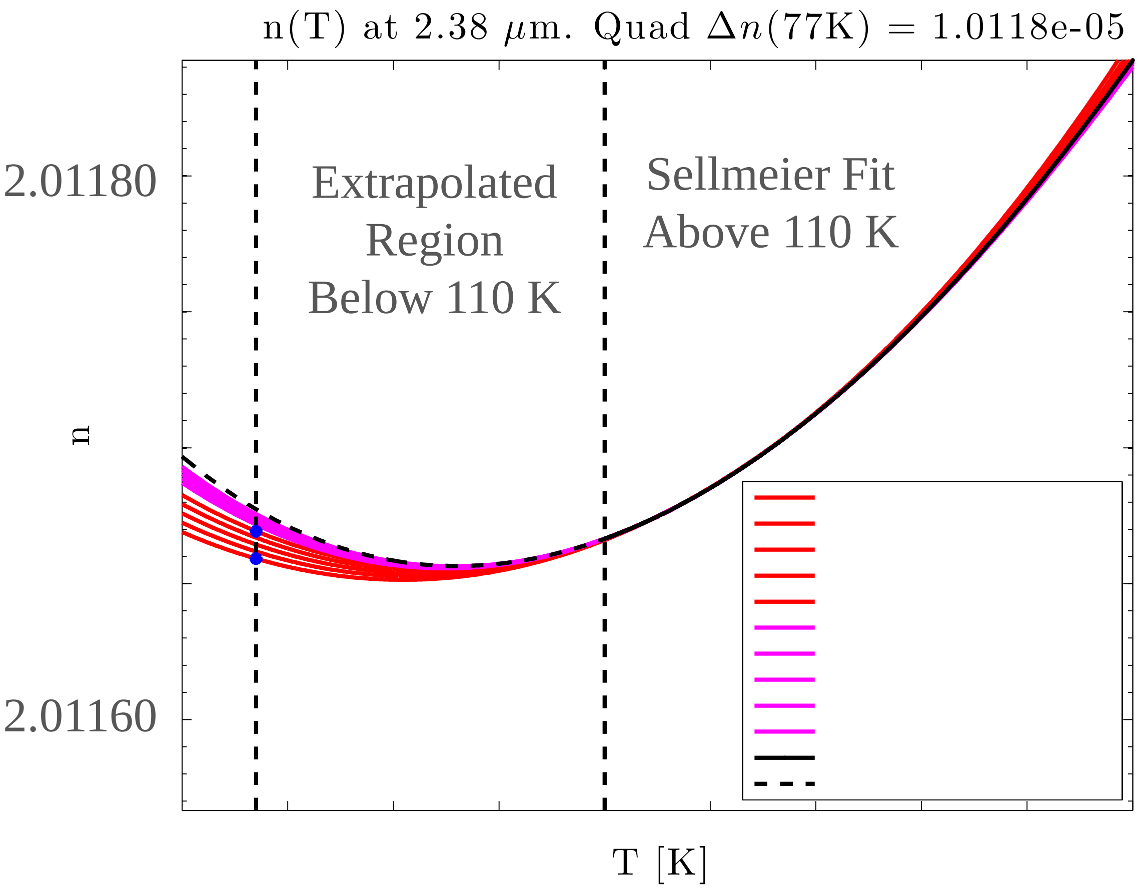
Unknown material properties:

- Cryogenic Index Data
- Thermal Expansion to cryogenic temperatures
- Homogeneity of material





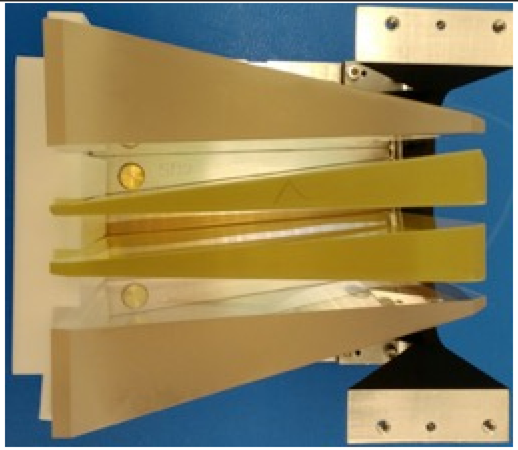
Goddard CHARMS test data

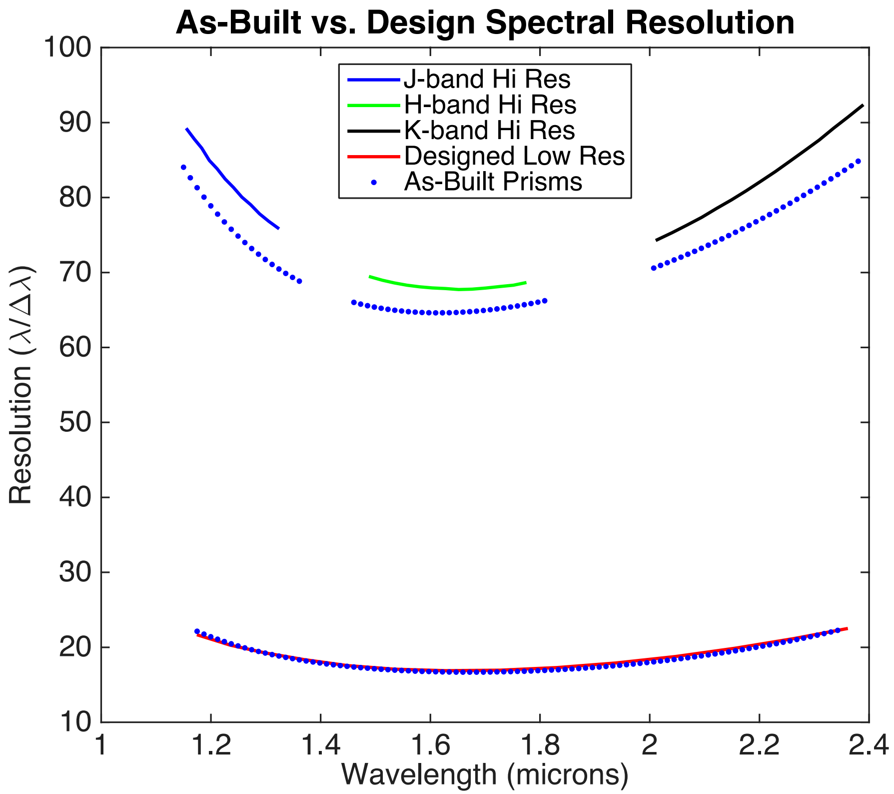


- Data for design down to 110K
- Extrapolations down to 77K
- Expecting the curve to flatten out at below 110K
- Subsequent index measurements change below the curve profile

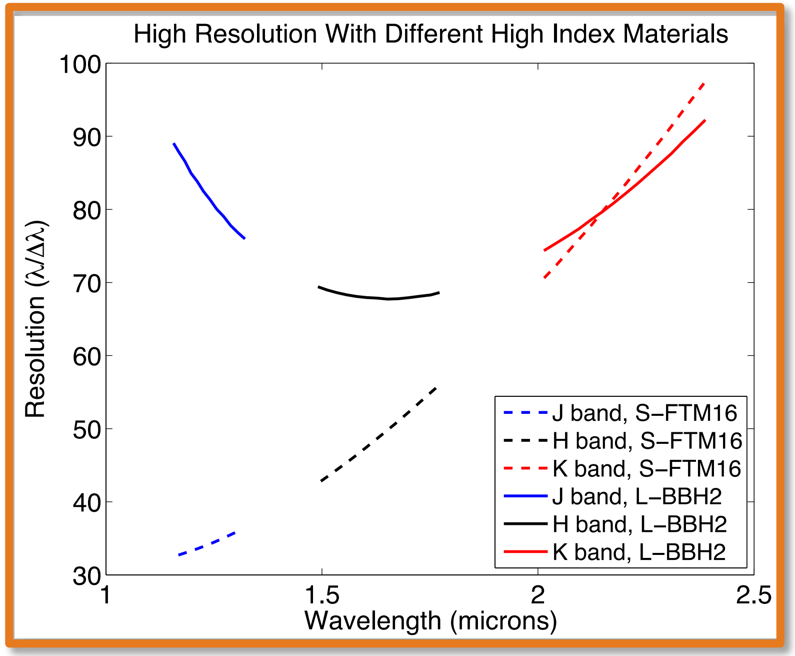
Fits to As-built Spectral Resolution

Mode	As-built	Design
J	75.2	82
H	65.2	69
K	77.1	82
Broadband	18.4	19



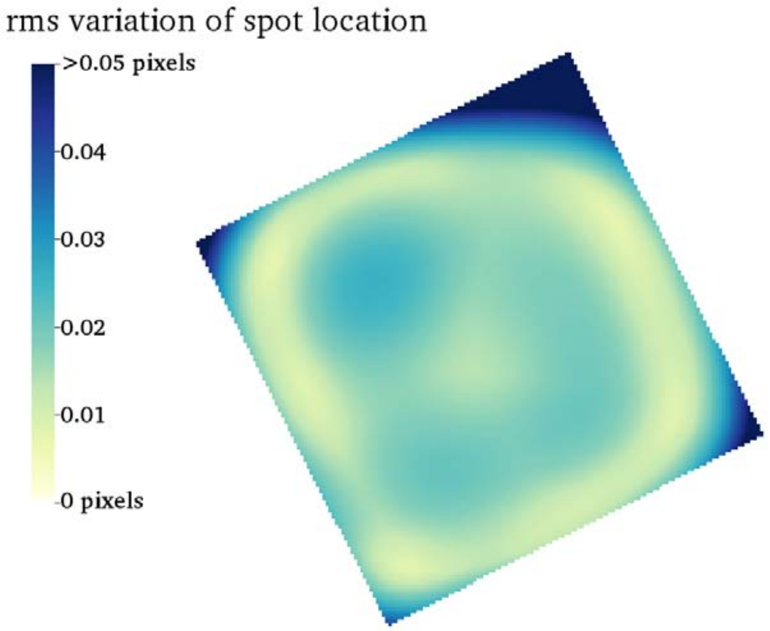


Fits Computed by Tim Brandt for Pipeline

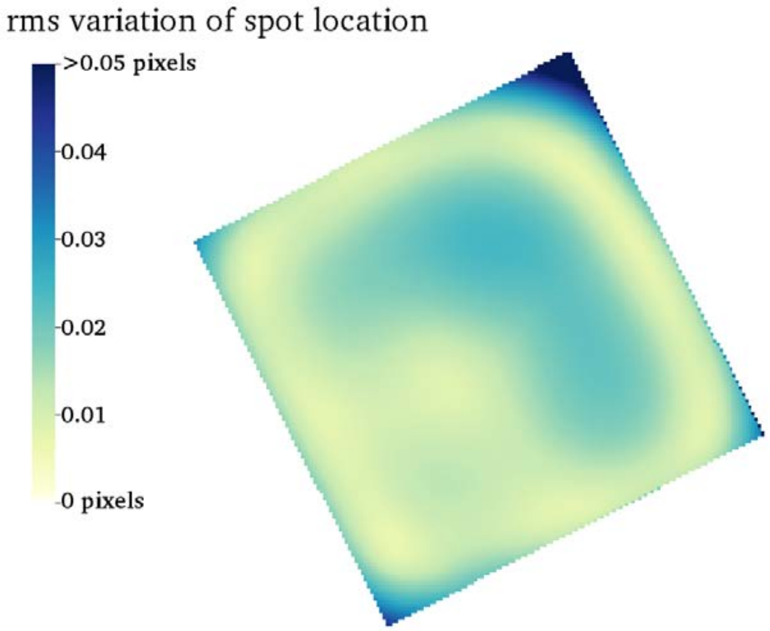


Repeatability

- Test Methodology:
  - Move prisms in and out several times
  - Measure root-mean-square scatter of lenslet spot positions at 1150, 1800 nm



Low-Res Repeatability, 1150 nm

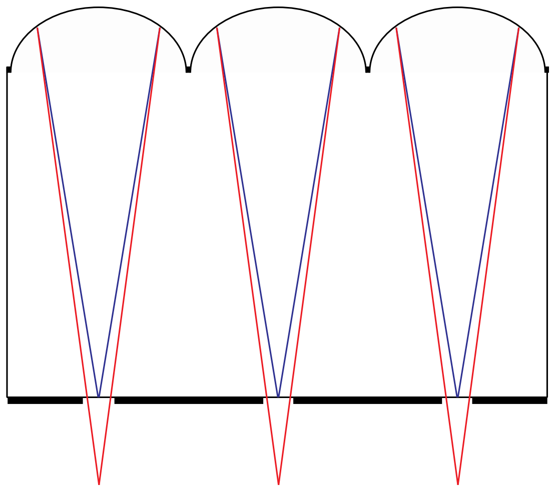


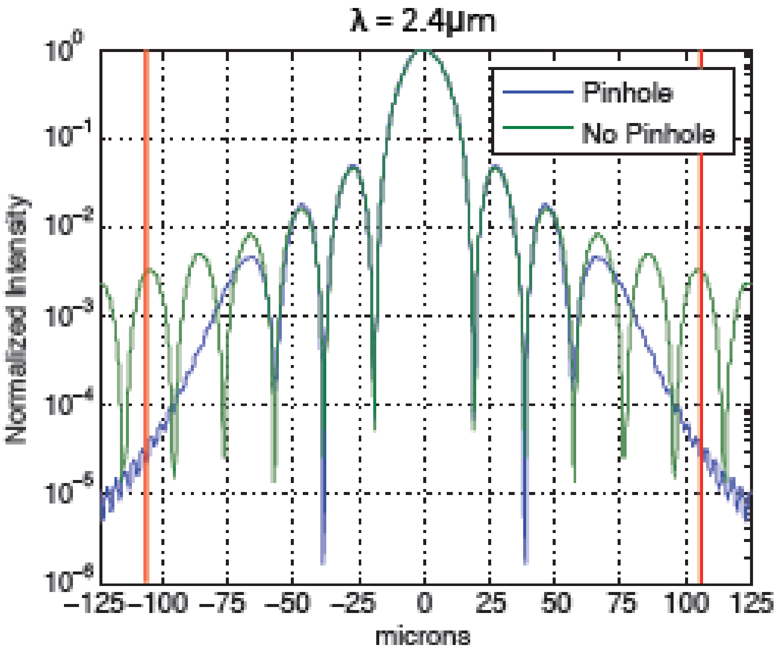
Low-Res Repeatability, 1800 nm

Based on Fits Computed by Tim Brandt on Monochromatic PSFs. Fits have high residuals at corners of field.

Mitigating Crosstalk

- Array of field stops ("pinholes")
- Clips diffractive contamination lenslets



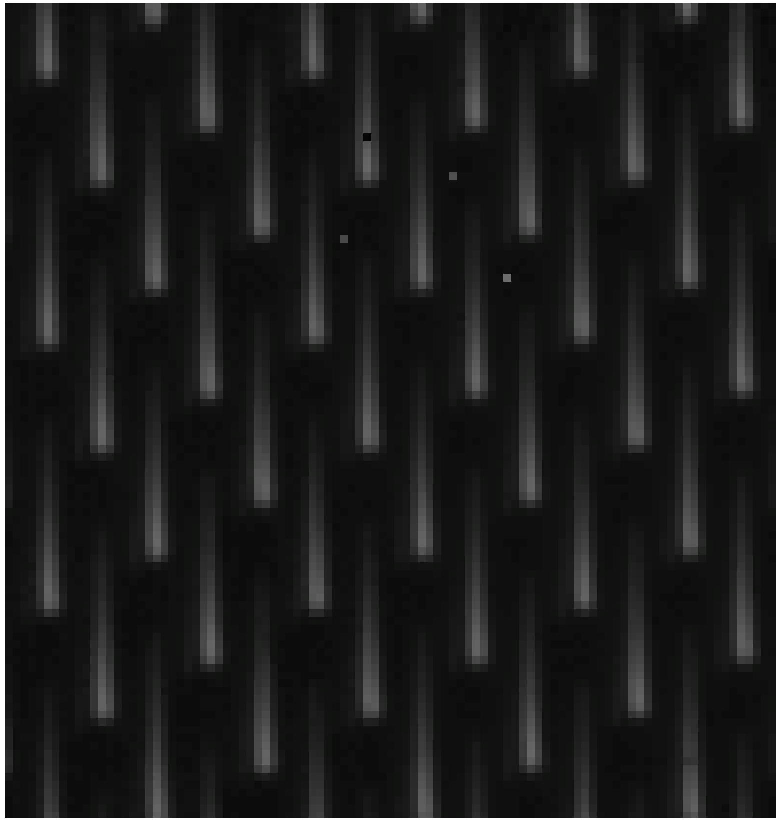


Impose Ensquared Energy requirements to capture Design, Alignment, Geometric distortion

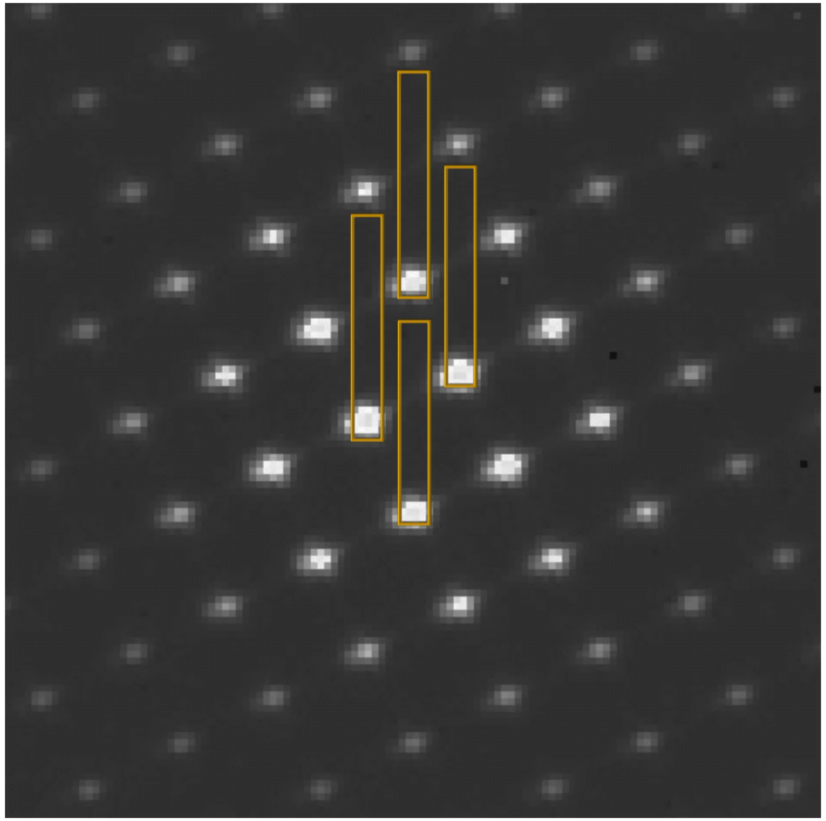
Wavelength [nm]	Ensquared Energy (180 x 180 um		
	Calculated from Measured Data	Design Value	Requirement
1150	0.980	0.995	> 0.97
1650	0.968	0.969	> 0.95
2400	0.950	0.951	> 0.94

ε	0.1%	0.5%	0.8%	1%
Min. EE	99.6%	98.2%	97.2%	96.5%

PSFs sampled with H2RG



K-band Flat Field Through Lenslet



2370 nm PSF through Lenslet Array

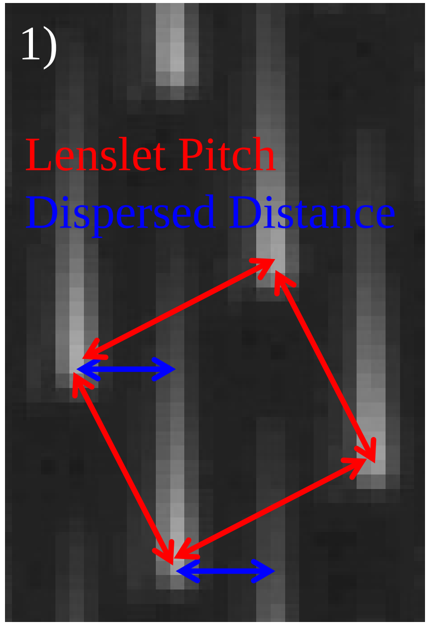
Crosstalk Performance

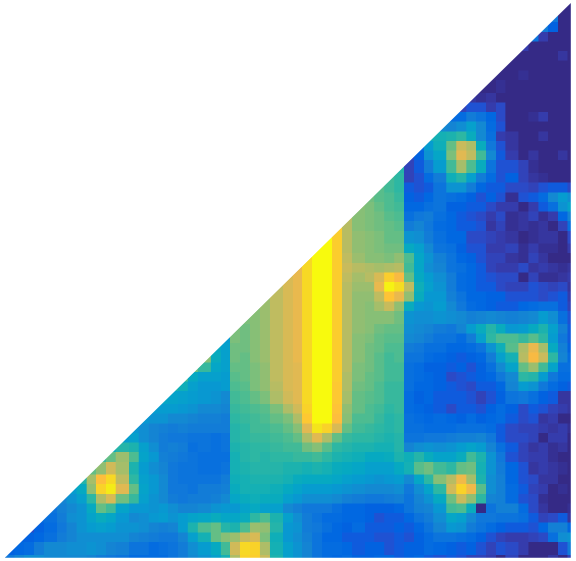
1. Adjacent spectra contaminate each other's spectra
2. Variance in target spectrum makes the problem worse
3. Careful control of wavefront+pinhole array mitigates crosstalk

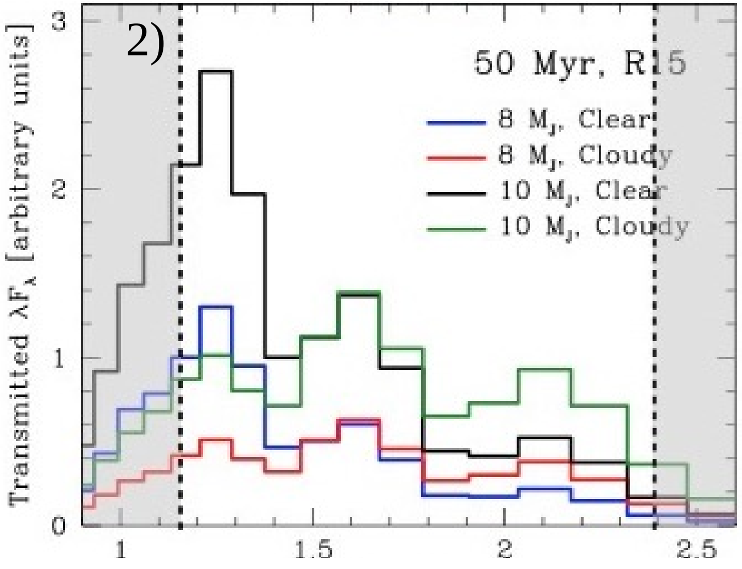
   <u>Integrated crosstalk in CHARIS estimated to be <4%</u>

   <u>Even better after PSF fits are accounted for in extraction</u>

This result is entirely due to diligence in tolerances and requirements through entire optical train.







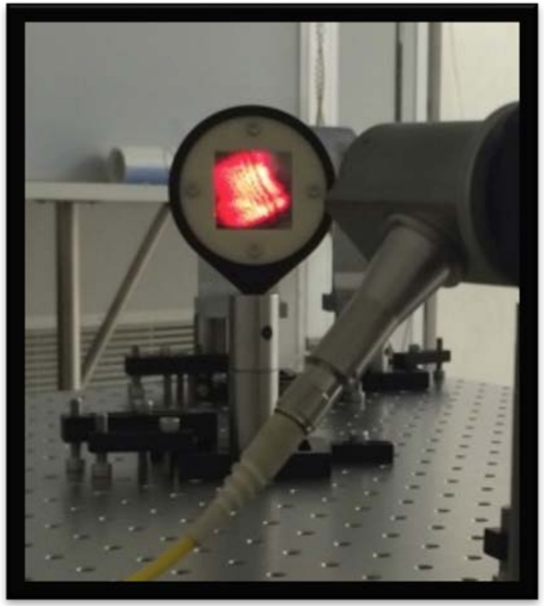
Spiegel&Burrows Warm Start Models

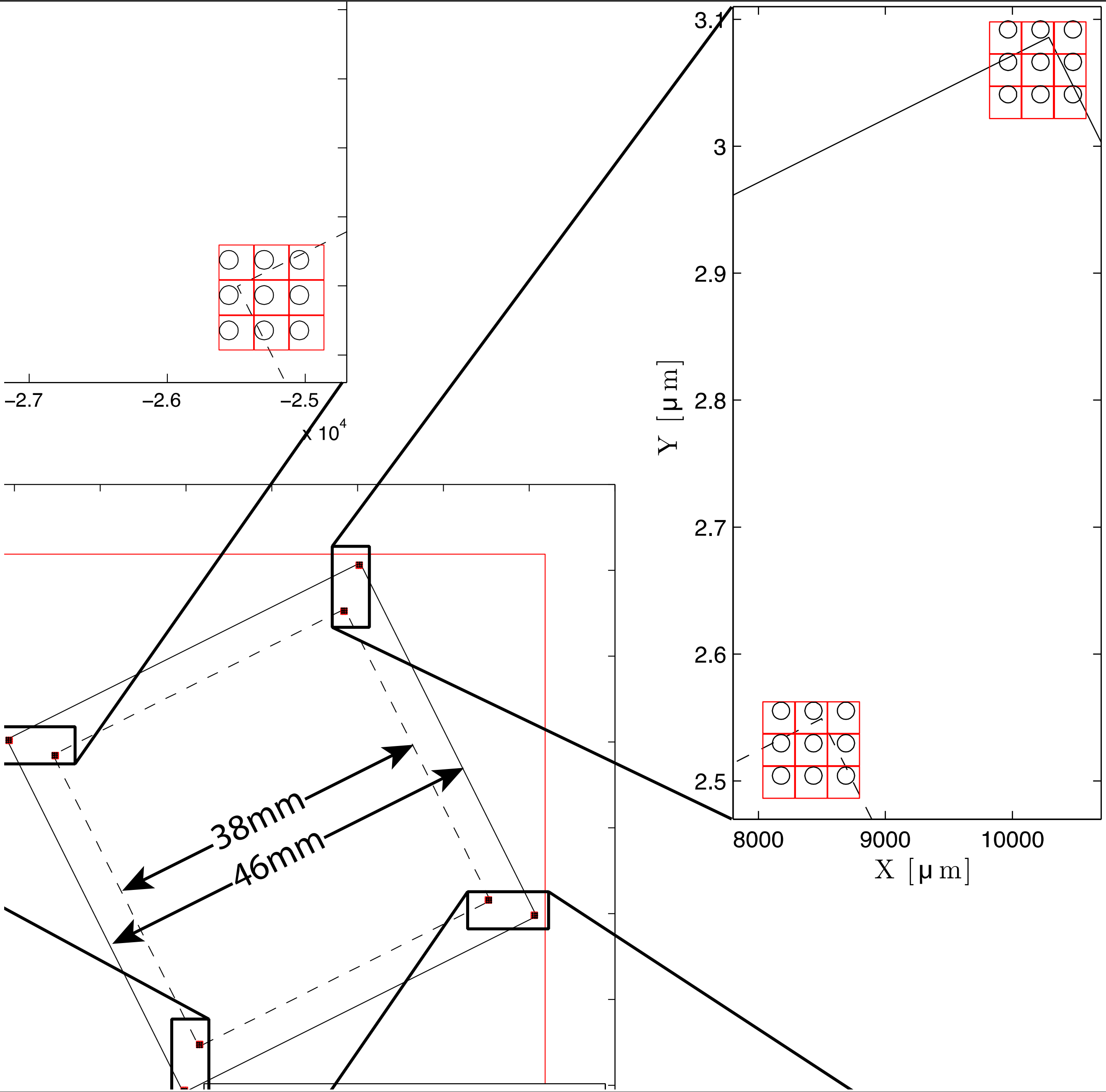
Lenslet PSFs

Solution:

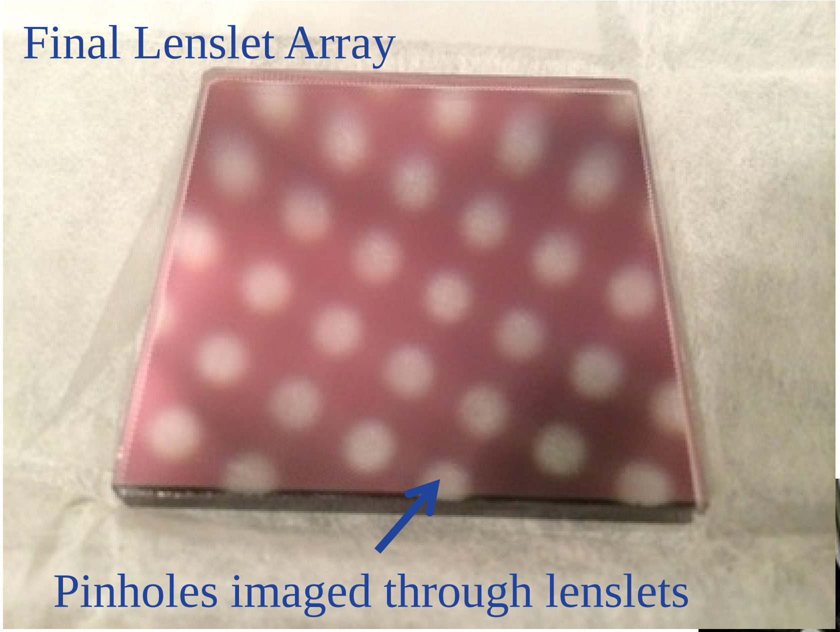
- Use many lenslets t
  oversampled lenslet PSFs
- Lenslet PSFs vary o
  field, but in a smooth,
  measureable, and
  reproducible way
- Bottom line:
  We can measure our lenslet PSFs extremely well even with some undersampling.

Telecentric Correction of Pinhole Positions

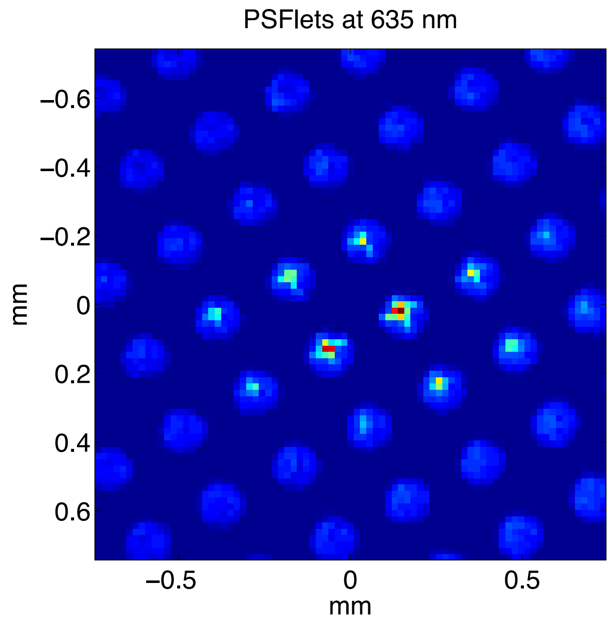


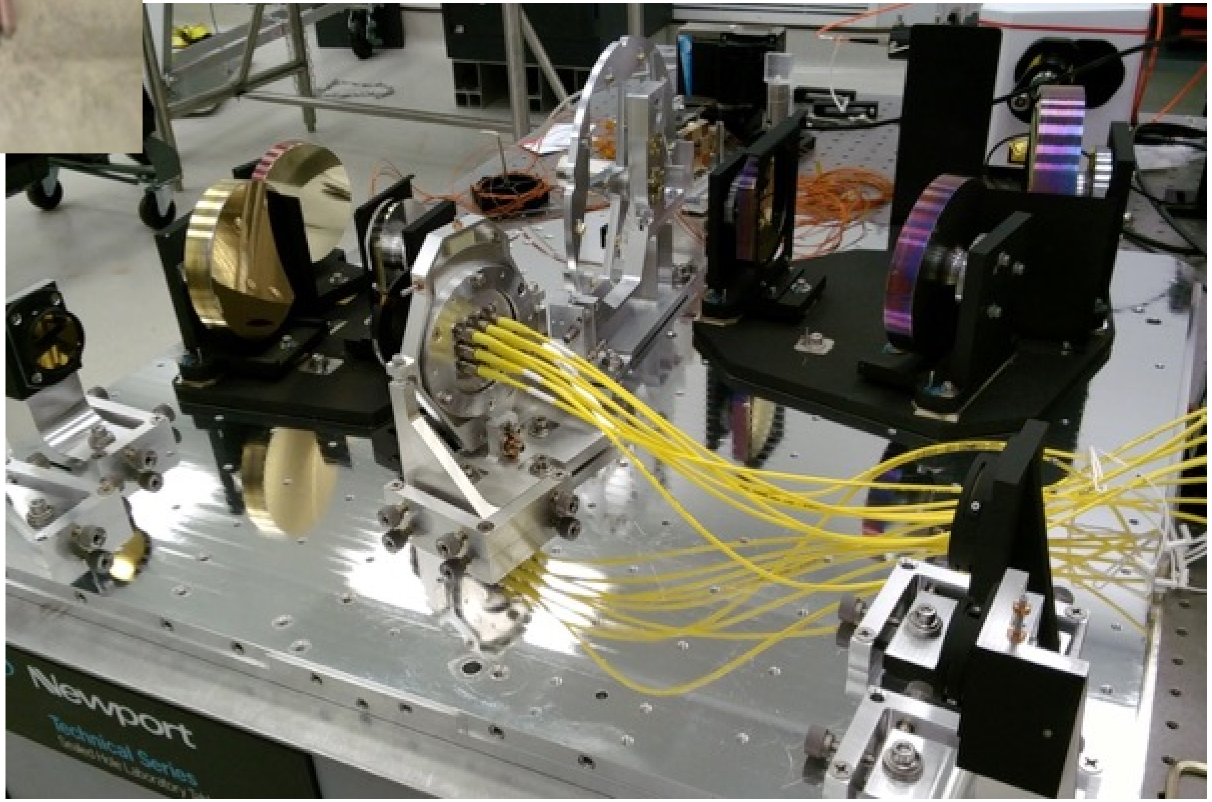


Alignment and Imaging of Lenslet Output



- Collimation using fiber array and custom pinhole arrays in visible light
- Tip-Tilt and Focus are locked to maximize stability
- Pinhole throughput checked in visible light





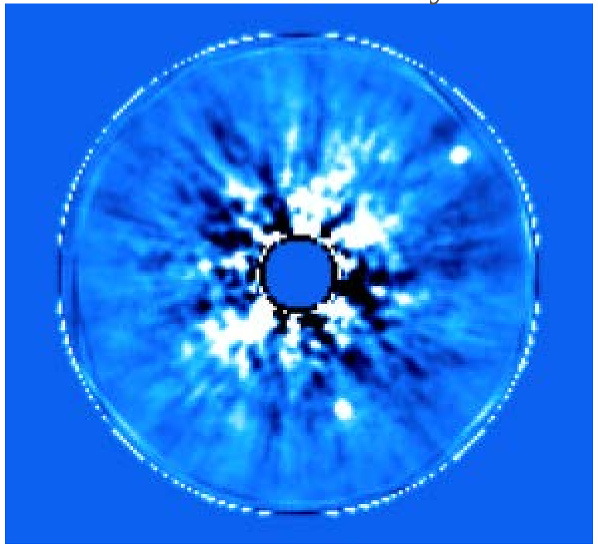
Brown Dwarf HD1160

- DM Satellites
  - Astrometric Calibration
  - Photometric Calibration
- Occulted Star
- Brown Dwarf

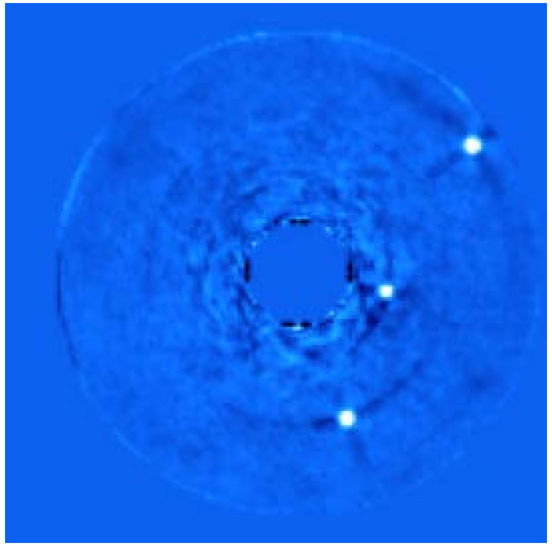
Broadband data by Jeff and Tyler
Pretty GIF made by Tim

CHARIS First Detections and Analysis by the Team

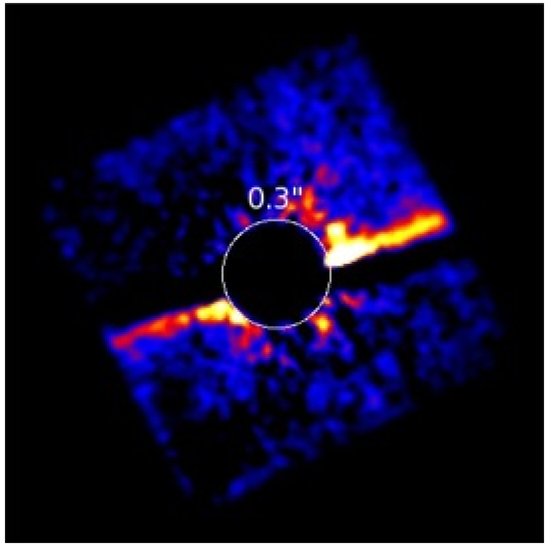
HR8799 ADI only



HR8799 ADI + SDI

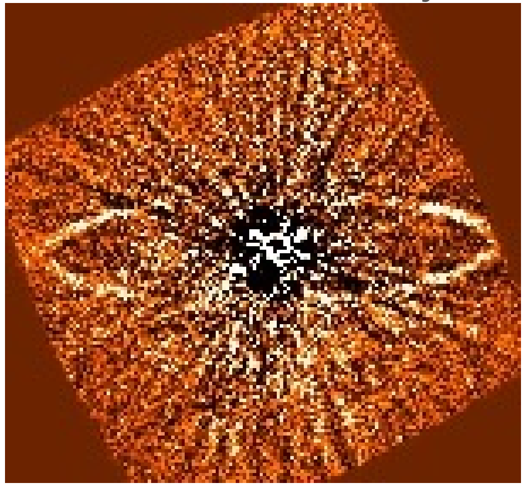


HD32297 Roll Subtracted

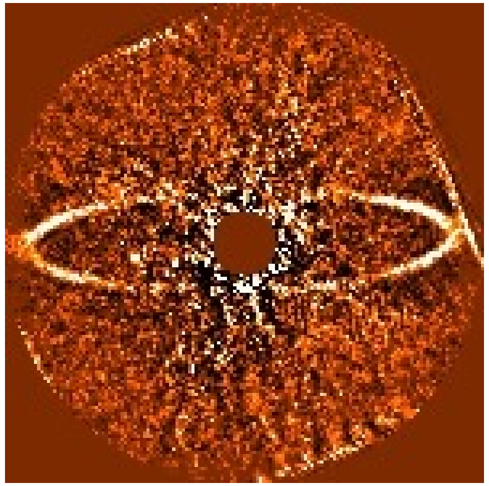


ADI+SDI detection of HR8799 c,d,e at SNR of 50, 35, and 15 respectively (~2-3 x 10^{-5})

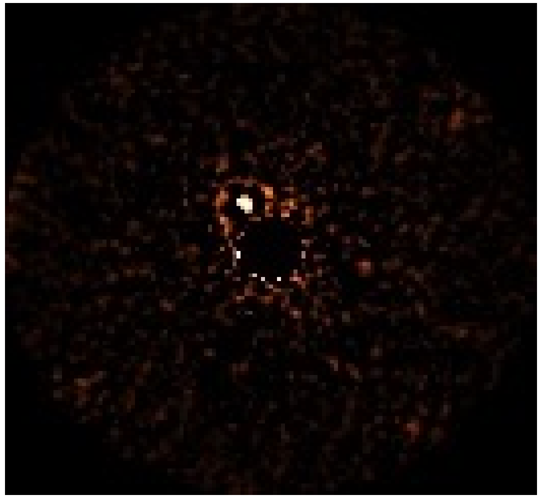
HR4796A - ADI only



HR4796A – ADI+SDI

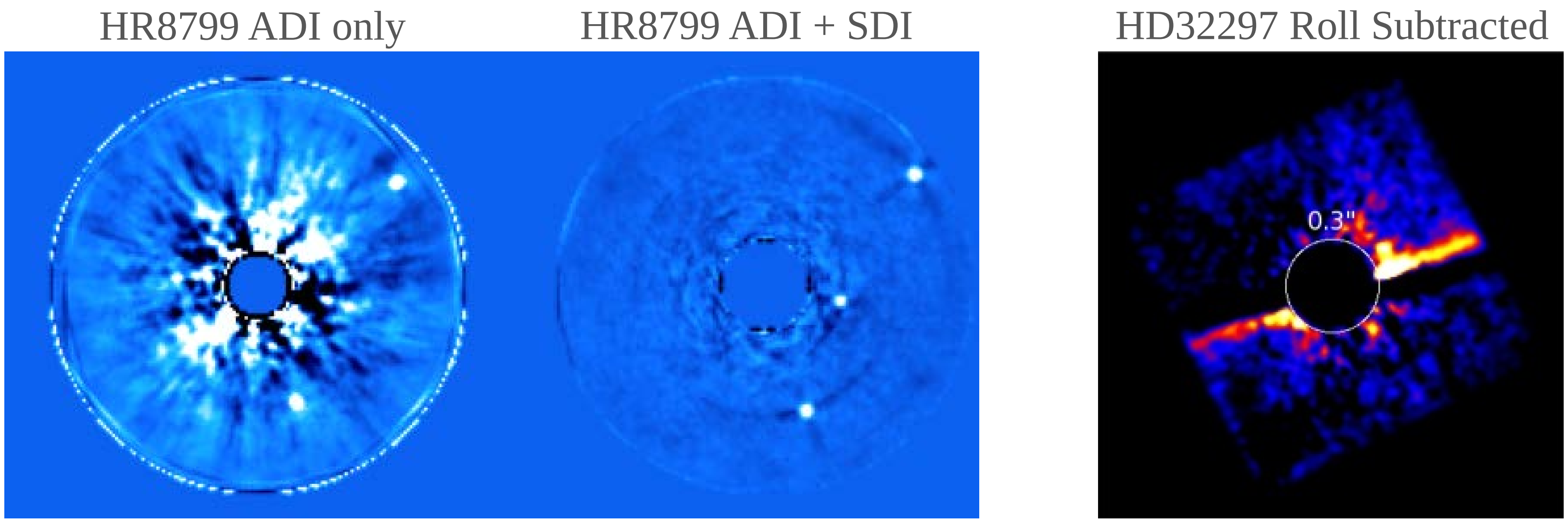


HD91312 K-band Slice

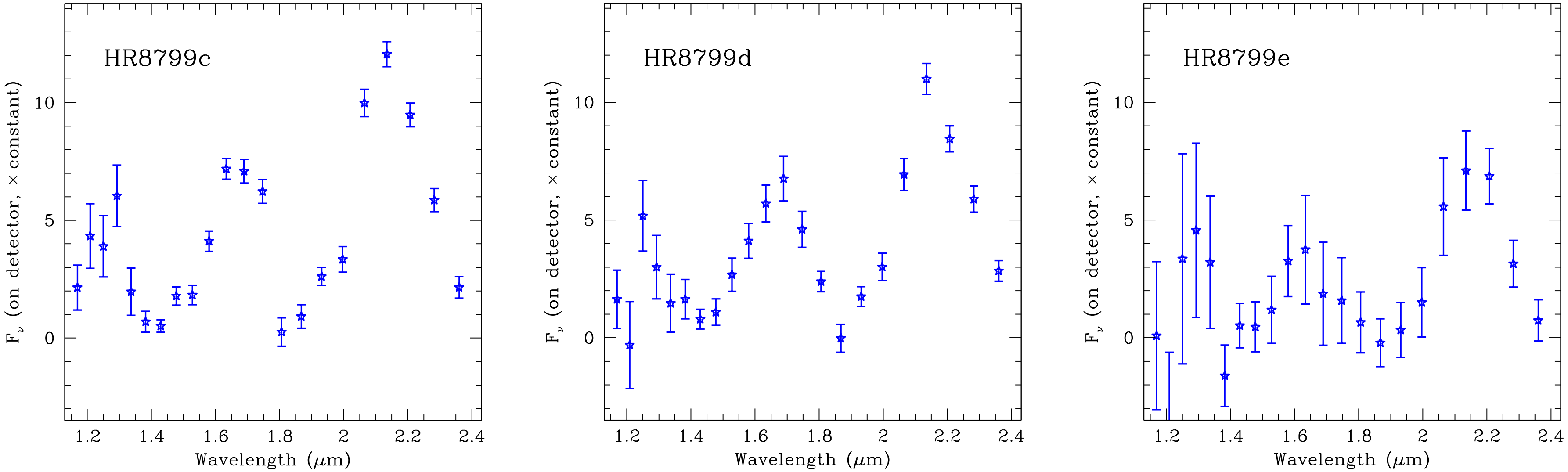


HR8799 preliminary data processing by Tim Brandt, HD32297 Processing by Thayne Currie, Quick HR4796A and HD91312 analysis by M. Rizzo et al.

The Science: CHARIS First detections

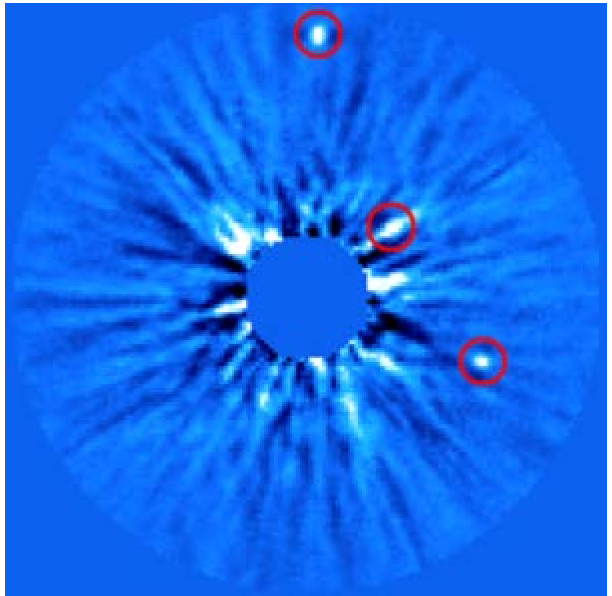


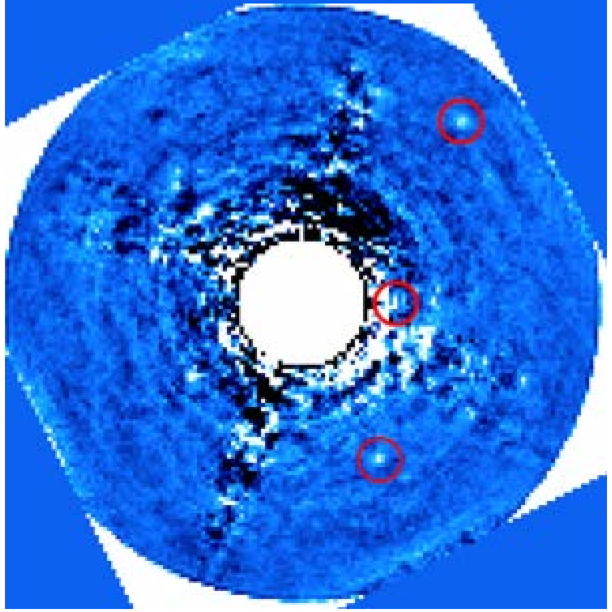
ADI+SDI detection of HR8799 c,d,e at SNR of 50, 35, and 15 respectively (~2-3 x 10^{-5})

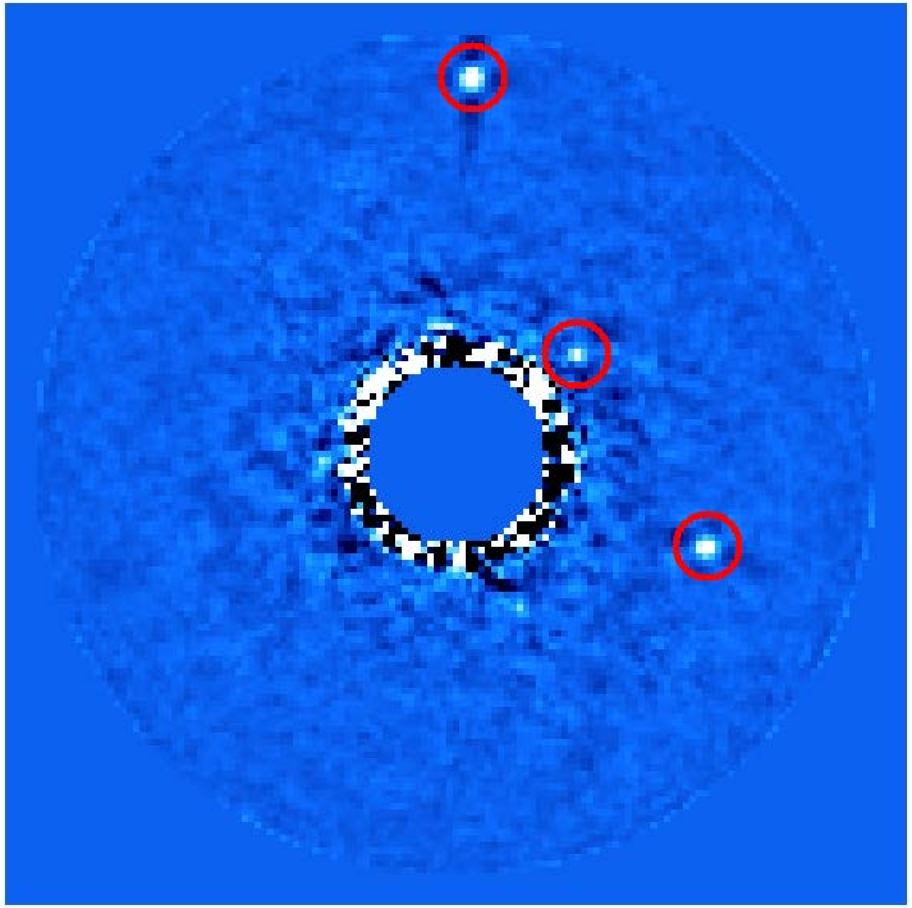


HR8799 preliminary data processing by Tim Brandt, HD32297 Processing by Thayne Currie

The Power of Low Resolution in Post-Processing



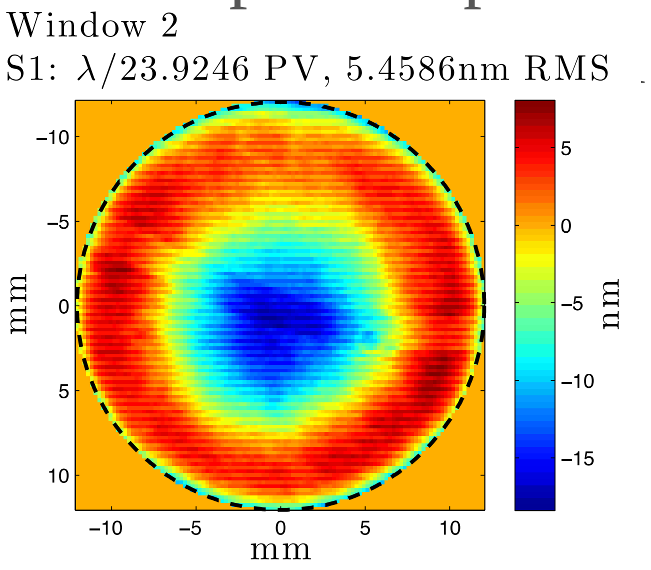


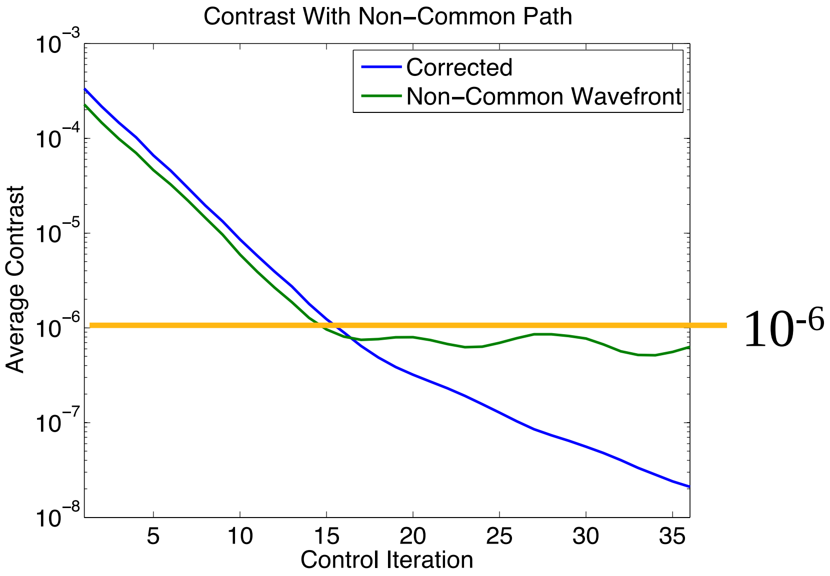


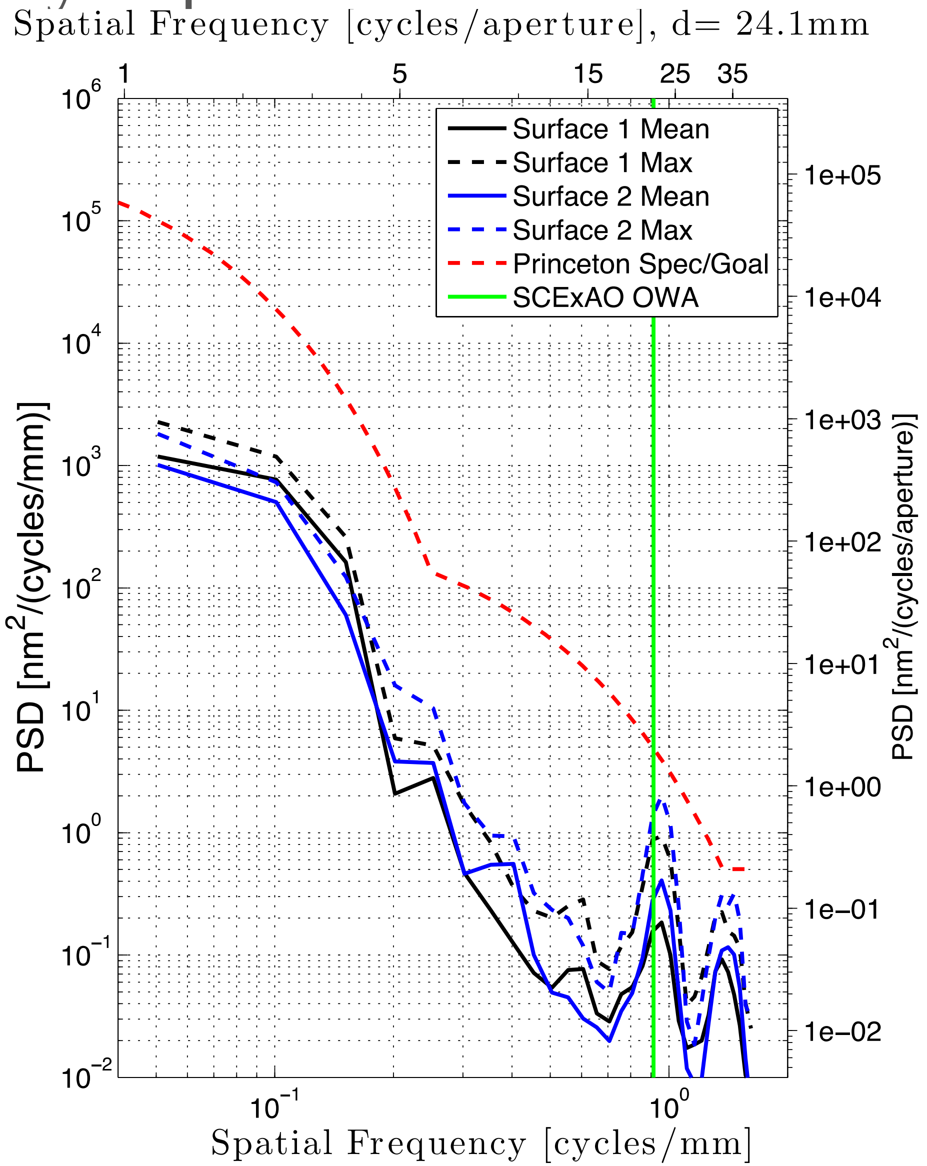
HR8799 c – 40 sigma detection
HR8799 d – 25 sigma detection
HR8799 e – 5 sigma detection

Wavefronts: CHARIS

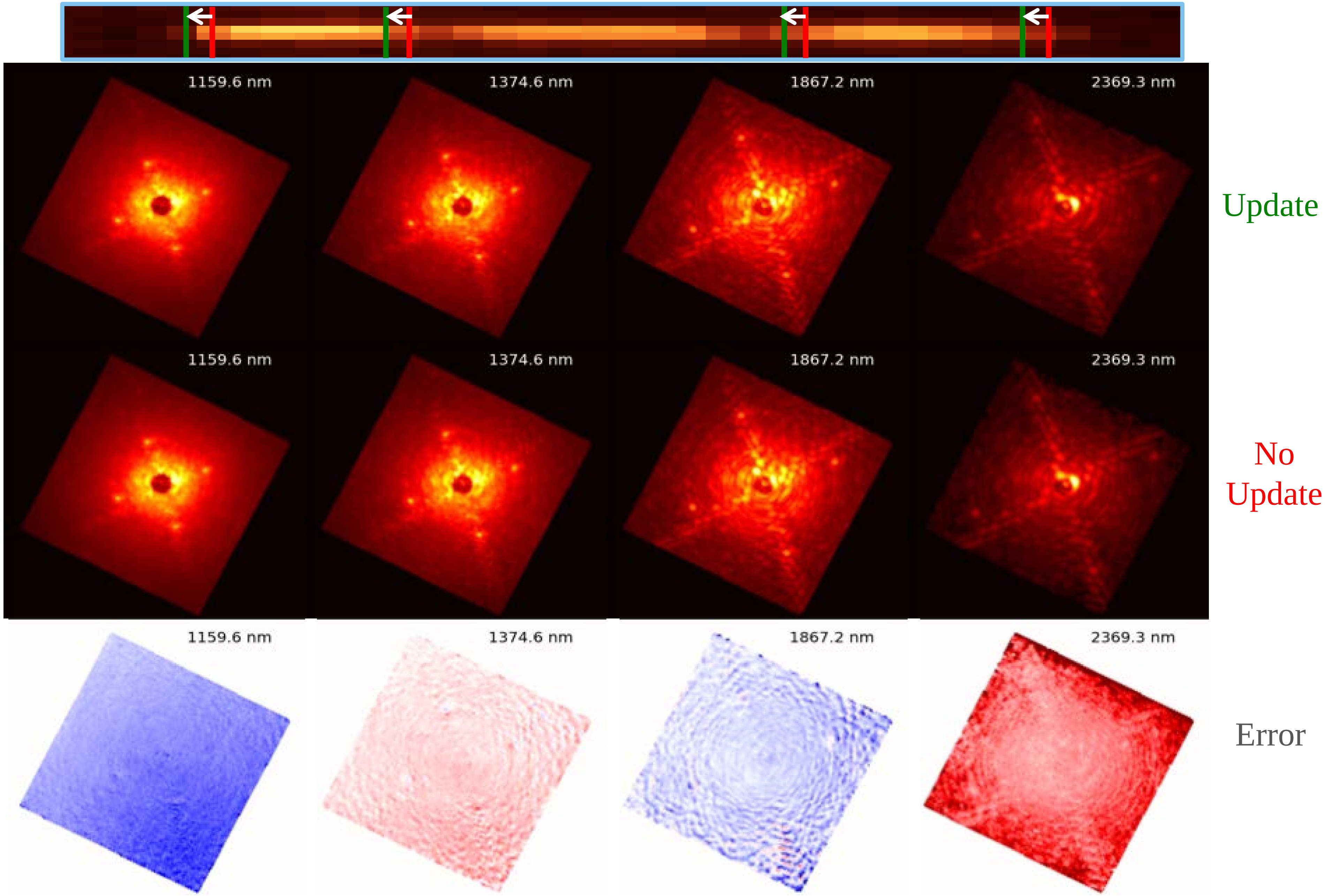
- Define power spectral density requirements of wavefront





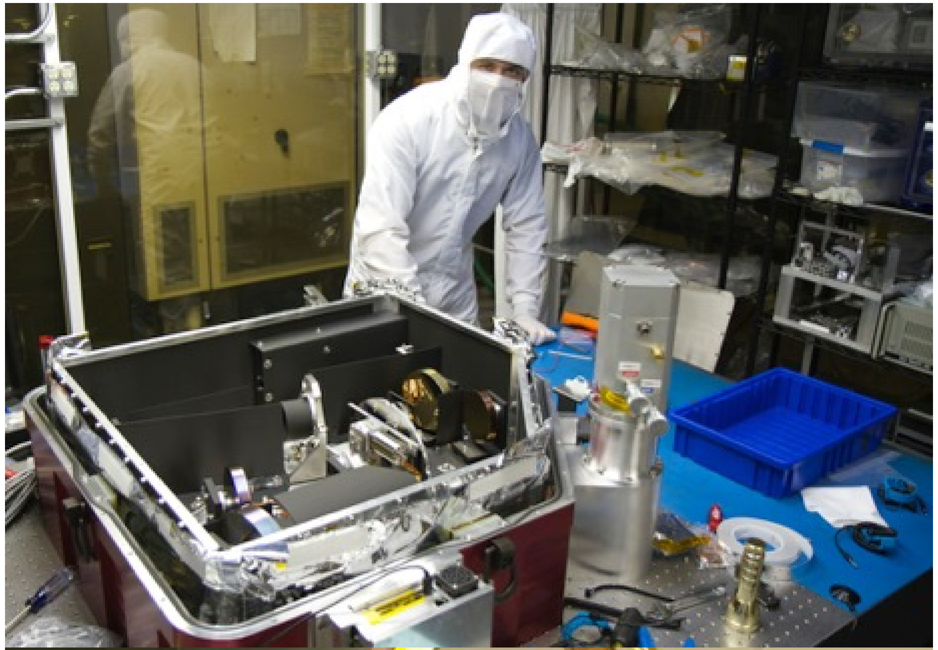


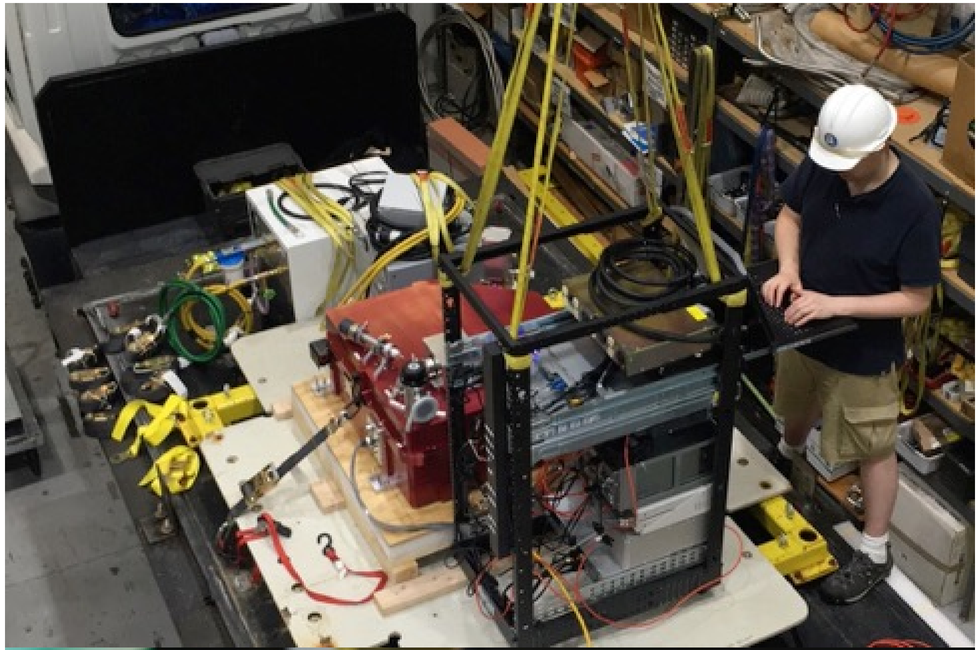
CHARIS: Impact of Image Registration



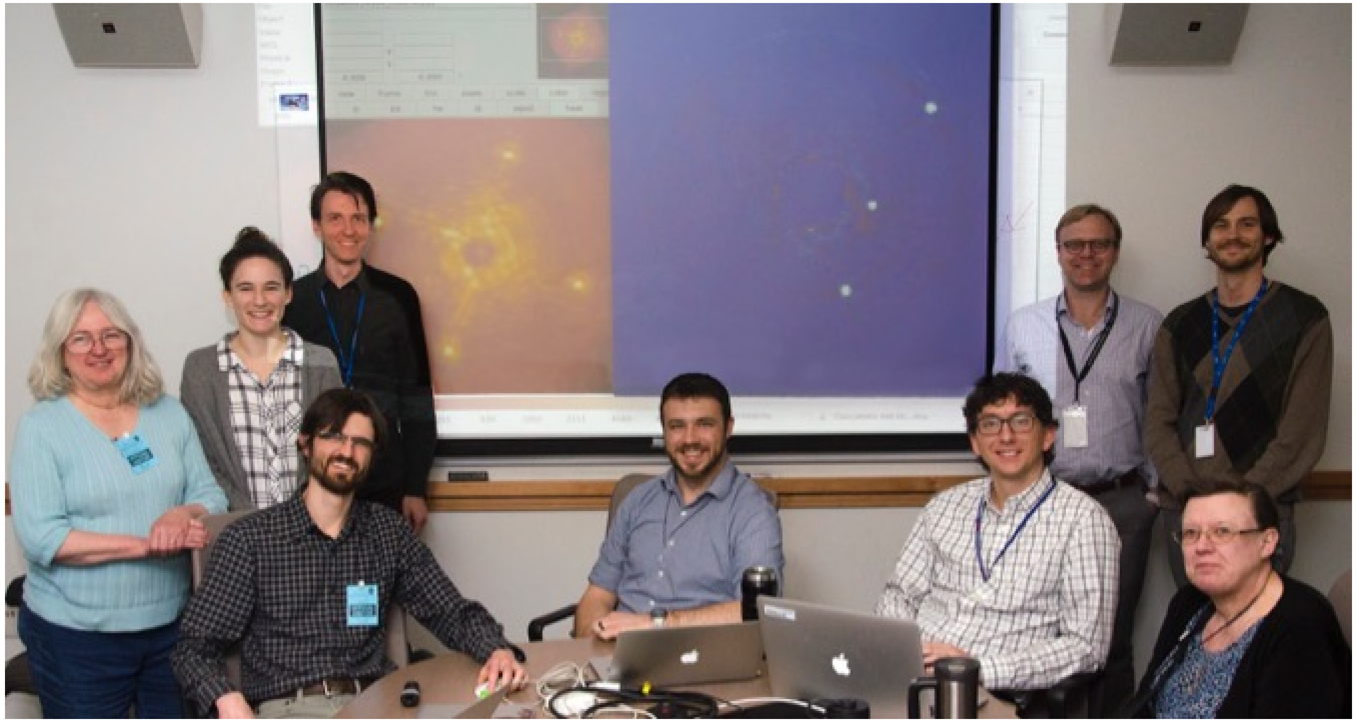
CHARIS Arrived in Hilo!

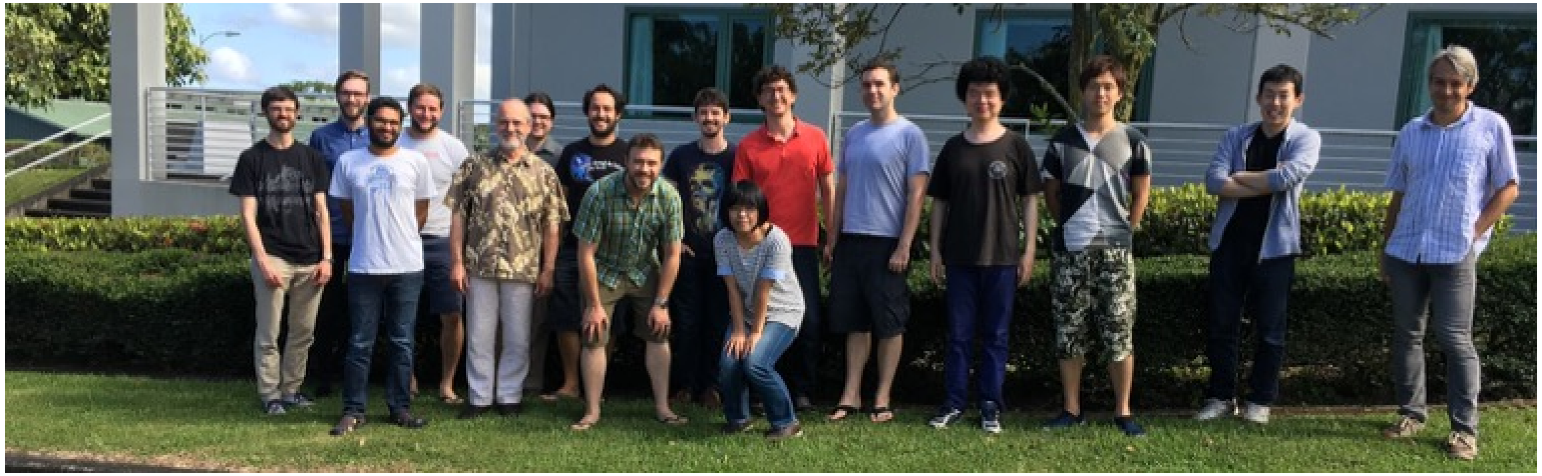
Rebuilding at Subaru



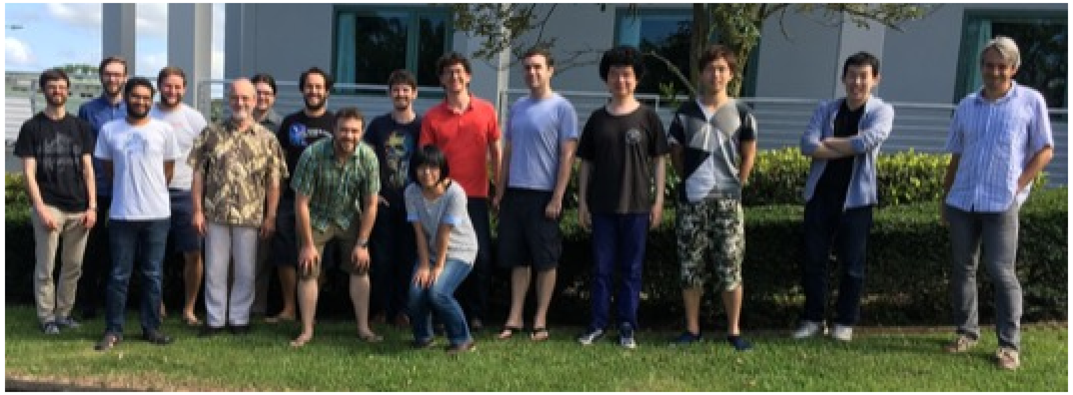


Data Workshops



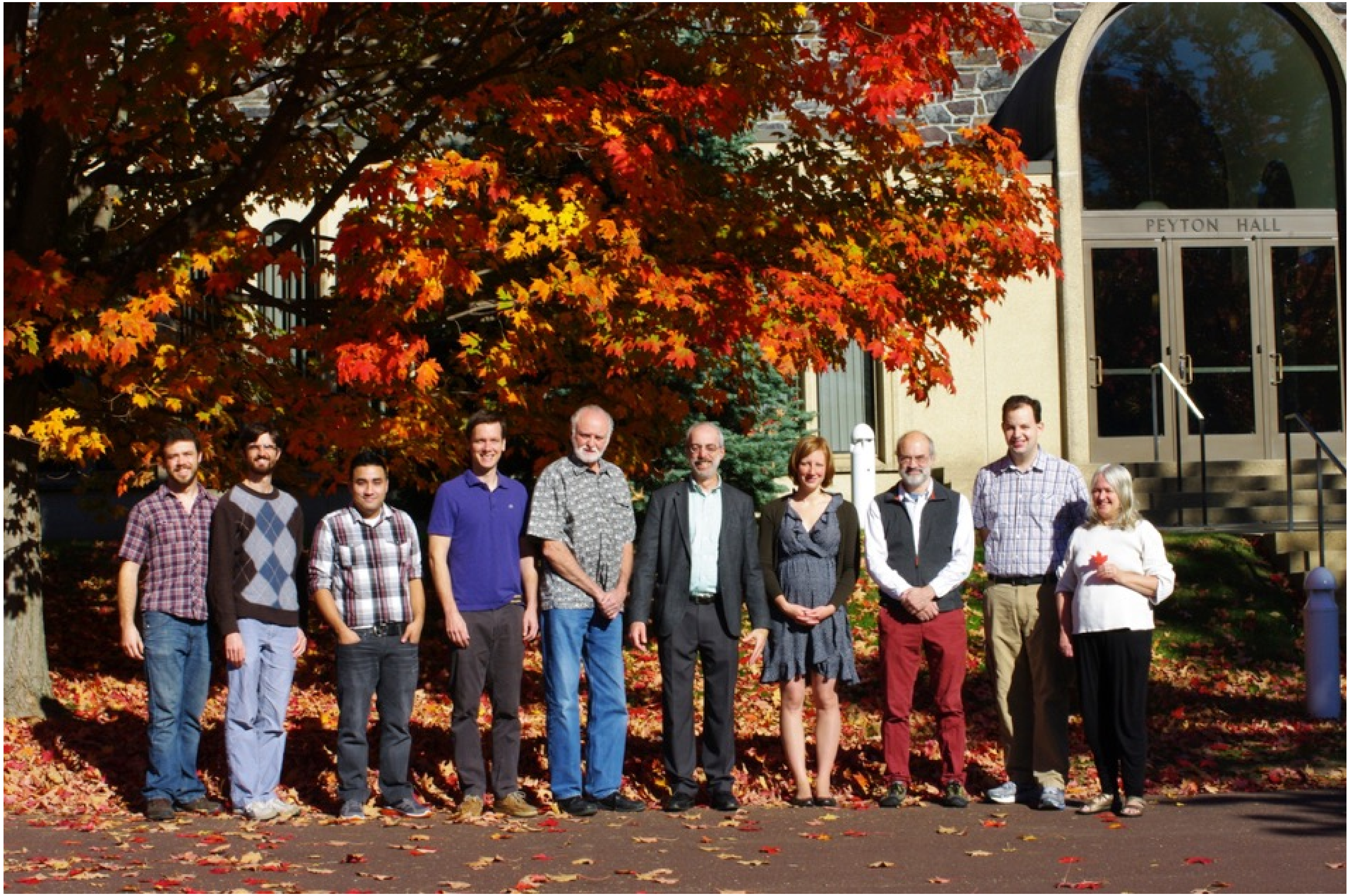


Subaru Data Workshop

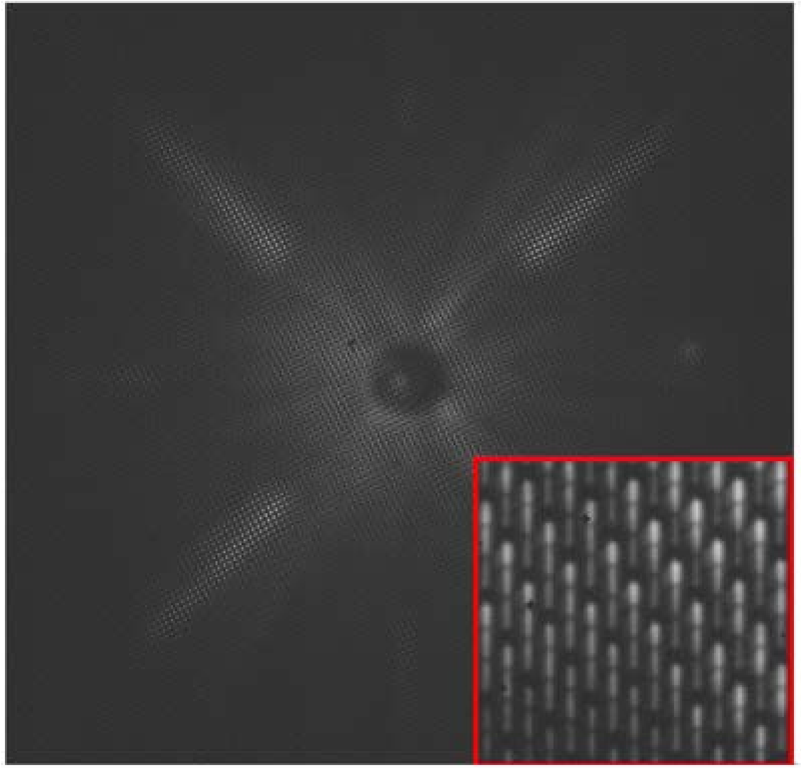


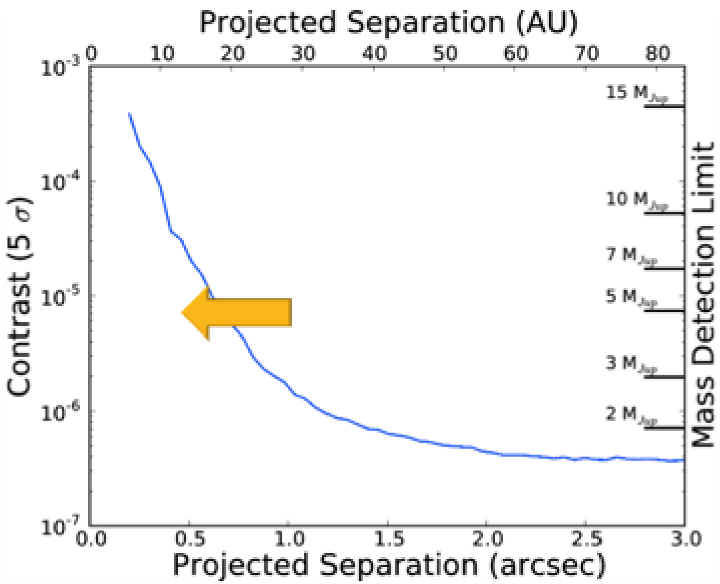
- 2.5 days
- Theory on ramps and cube extraction
- Everyone installed and tested cube extraction
  - Built calibrations
  - Extracted data cubes from archived data
- Calibration procedures
- Short ADI/SDI tutorial
- **17** on-site participants
- **4** remote participants
- Ran on Linux, Mac, and Windows

Thank You

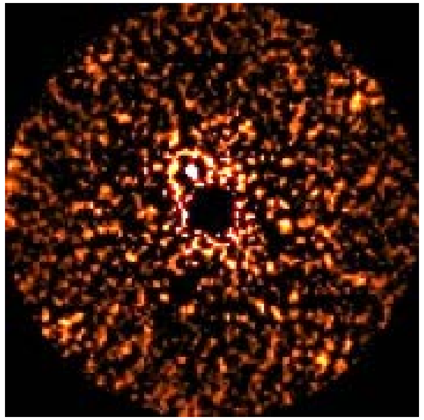


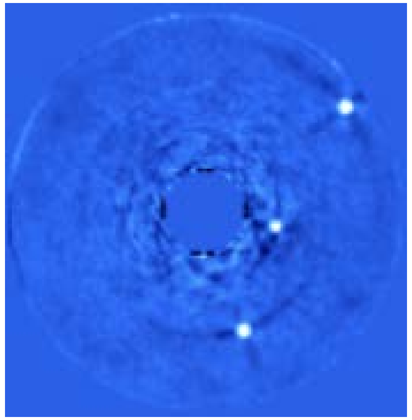
CHARIS Images and Contrast Goals

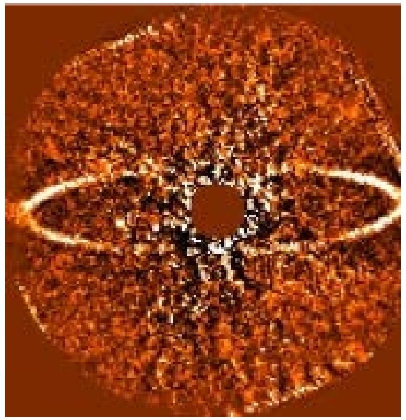




SEEDS Contrast Estimate Courtesy Michael McElwain and Tim Brandt and SEEDS team







Thanks to my team members Tim Brandt, Jeff Chilcote, and Maxime Rizzo for Processing these Images